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Practical Radiation Monitoring

National
Measurement
System

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Practical Radiation Monitoring

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National Physical Laboratory

Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of the Managing Director, NPL,

by Dr Steven Judge

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Peter Burgess	Nuvia Ltd
Rob Corby	Magnox Ltd
Denise Delahunty	RRPPS Birmingham
Steven Judge	National Physical Laboratory
Lynsey Keightley	National Physical Laboratory
Clare Lee	National Physical Laboratory
Tony Richards	Consultant (Leeds)
John Simpson	Consultant
Mike Woods	IRMC
Ludovic Chevallereau	Amec Ltd

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Foreword

This *Good Practice Guide* has been written by a working party of experts from the UK Ionising Radiation Metrology Forum*, it replaces the first issue published in 2002. It describes procedures and methods for assessing radiation levels, outlines the thought processes needed to carry out the measurements and gives practical advice. The methods described are general and based on currently accepted good practice.

We hope the document will standardise the approach to radiation monitoring. We feel the document is meant for everyone involved in radiation measurement, as a refresher for those who know, and as a guide for those who aren't familiar with the topic, particularly new entrants to the field.

The statutory requirements for the designation, control and monitoring of areas are stated in national regulations. In order to comply with the statutory requirements, all employers who work with ionising radiation must ensure that radiation areas are adequately monitored by suitably qualified and experienced people, using calibrated instruments able to measure the type of radiation in use.

The procedures described in this *Guide* are for general application; different procedures may be used if appropriate but guidance on these must be obtained from a Radiation Protection Adviser.

* The Ionising Radiation Metrology Forum is organised by the NPL for the purpose of discussing Radiation Measurement and Instrumentation. Members of this Forum form the Working Party that drafted the second issue of this Good Practice Guide on Practical Radiation Monitoring.

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1 Introduction

The responsibility for radiation protection rests with the employer. The national and international regulatory bodies play an active role in ensuring that facility owners, employers, operators and contractors who use ionising radiation, or are engaged in the removal of radioactivity, observe the current legislation[1,2] and follow suitable work methods.

This *Good Practice Guide* recommends methods and procedures for the practical radiation monitoring of any facility. The recommendations are largely based on common practice determined from discussions with the radiation community and a workshop in which delegates from the nuclear, medical, education and defence sectors took part.

This *Guide* outlines the thought processes and steps that will need to be taken to ensure compliance with statutory requirements. It provides assistance in defining the problem, identifying a strategy and selecting instruments for a monitoring programme. In addition, it gives guidance on monitoring techniques and the interpretation of results.

The procedures and methods given in this document have no legal standing and companies and contractors may implement their own schemes, provided that they ensure compliance with the relevant regulations[1,2]. These recommendations have, however, been developed by a committee of experts and the combined deliberations of the Ionising Radiation Metrology Forum (IRMF). The IRMF holds the view that the adoption of this guidance should normally ensure compliance with statutory obligations.

This document covers surface contamination and dose rate monitoring only. It does not include advice on more specialised monitoring such as air monitoring, waste monitoring, gas monitoring or personal dosimetry. Guidance on further types of radiation measurement is available in GPG14[3] (calibration of portable dose rate and contamination monitors), GPG29[4] (calibration of installed monitors), GPG34[19] (non-destructive assay), GPG82[20] (testing of airborne particulate monitors) and GPG113[21] (testing of electronic personal dosemeters); a further guide on the testing of tritium monitors was nearing completion at the time of publishing this Guide[22]. Information on assessing uncertainty in radiological measurement is provided in GPG49[23].

2 Defining the problem

Think through any situation in which radiation monitoring is required before the monitoring begins.

In many organisations there will be standard procedures that state how routine radiation protection monitoring should be done. The monitoring will take place in familiar areas, carried out by an organisation's own staff, using its own monitoring equipment and reporting system.

In other circumstances, however, there will be no standard procedures in place and help may be required to get the project started. The surroundings may be unfamiliar and additional equipment may be needed. Discussions will be necessary to clarify what measures must be taken and, if necessary, to draw up a written procedure.

The reasons for carrying out the work will have to be established and the following questions need to be asked:

Who - is the organisation requesting the investigation and measurements? Is the organisation an outside company or an internal group?

What - is being monitored? Is it a radiation or contamination survey? This may affect the dose rate range, the required levels of detection, the degree of complexity involved and the corresponding investigation time. Is the monitoring of sinks and drains required? Is the area controlled, supervised or undesignated?

Why - is the monitoring needed? Is it a contamination assessment, an incident, a change of use of the area or some other reason?

When - will the monitoring take place? This will influence the measurements, as ambient dose rates may vary and other operations taking place in the vicinity may affect the results. Are access times restricted?

There may be many factors which will affect WHO, WHAT, WHY and WHEN. It is not possible to outline all the aspects that need to be considered at this stage in the investigation.

3 Gathering information

IN THIS CHAPTER

- Initial investigations
- Source characteristics
- Environmental characteristics
- Worker discussions
- Records

Before beginning any investigation (contamination survey, radiation survey, accident investigation, etc) establish the extent and nature of the problem.

Beware! The magnitude of the problem may be hidden.

It is important to gather information of sufficient detail in order to ***plan the investigation fully*** and avoid missing crucial aspects or having to backtrack unnecessarily.

Detailed information and planning at an early stage will help to ensure that the exercise runs smoothly and efficiently. It also provides the opportunity to ***assess whether it will be necessary to obtain equipment or services that are not readily available*** – this could be of benefit if the exercise is likely to be time-consuming, for example, monitoring laboratory contamination.

At this stage it can be useful to ***establish working practices*** in the area under investigation. For example, are contamination checks done immediately and any contamination removed or are the checks done at the end of the working day? Is a low level of contamination permitted?

Points to consider

Which radionuclides are likely to be present and what types of radiation do they emit?

Are the sources sealed or unsealed? If unsealed, what are their chemical forms?

What activity levels are expected?

Are the sources solid, liquid or gas?

What is their toxicity - radiological, chemical, biological?

Is the source a machine, such as an X-ray set?

Is there any documentation available (radiation protection survey reports, work records, laboratory instructions etc)?

Are there any experienced personnel available who work, or used to work, in the area?

What processes take place in the area?

3.1 Initial investigations

Establish and document the current conditions. Obtain information about aspects such as radionuclides used, sealed sources used, X-ray work, the number of workers, the source activity, emissions and volatility of the radionuclides in use.

At this stage, ***any unusual aspects of the work should be noted***. These aspects should include anything that may create assessment problems. Examples would be the low temperature treatment of sealed sources in Mössbauer work or unusual beams in accelerator work or radiotherapy.

Particular attention should be given to radionuclides that may be difficult to monitor. These would include low energy b emitters, a emitters, electron capture radionuclides and others.

Early identification of the measurements that will have to be made will show any conditions that may make an apparently simple investigation more difficult.

3.2 Source characteristics

Careful consideration must be given to the radionuclides that are in use. At an early stage, think about the decay schemes and emissions in order to ***identify measuring equipment, which will detect the emissions with the appropriate sensitivity***.

It is important to recognise that the energy spectrum of particles or photons emitted depends upon the nature of the source. This is because the encapsulation material of a sealed source may remove some or all of the a or b particles emitted from the radioactive material, whereas with an open source, there is no encapsulation material and therefore less absorption.

The radiation received by the monitor can be different to that emitted from within the source.

There are a number of publications that list the half lives and main emissions from radionuclides, such as the *ICRP Publication 38*[8] and the *Table of Isotopes*[9]. There are also a number of recommended, freely available tools on the internet such as DDEP data[13] and RadDecay[14].

Table 1 lists some of the radionuclides in common use in the medical, research, nuclear and industrial sectors as sealed and unsealed sources.

Medical	Research	Nuclear	Industry
^{11}C	^{3}H	^{3}H	^{3}H
^{14}C	^{14}C	^{14}C	^{60}Co
^{13}N	^{32}P	^{35}S	^{137}Cs
^{15}O	^{33}P	^{36}Cl	^{85}Kr
^{18}F	^{35}S	^{51}Cr	$^{90}Sr+^{90}Y$
^{32}P	^{36}Cl	^{54}Mn	^{147}Pm
^{51}Cr	^{45}Ca	^{55}Fe	^{204}Tl
^{57}Co	^{55}Fe	^{60}Co	^{210}Pb
^{67}Ga	^{59}Fe	$^{90}Sr + ^{90}Y$	^{210}Bi
^{68}Ga	^{60}Co	^{99}Tc	^{210}Po
^{75}Se	^{63}Ni	^{131}I	^{226}Ra
^{81m}Kr	$^{90}Sr+^{90}Y$	^{137}Cs	^{232}Th
^{86}Ge	^{109}Cd	^{235}U	^{238}U
^{89}Sr	^{125}I	^{238}Pu	^{241}Am
^{90}Y	^{129}I	^{238}U	$^{241}Am+Be$
^{99}Mo	^{137}Cs	^{239}Pu	
^{99m}Tc	^{147}Pm	^{241}Am	
^{106}Ru	^{151}Sm		
^{111}In	^{152}Eu		
^{123}I	^{204}Tl		
^{125}I	^{226}Ra		
^{131}I	^{238}U		
^{133}Xe	^{241}Am		
^{153}Sm	$^{241}Am+Be$		
^{186}Re			
^{192}I			
^{201}Tl			
^{223}Ra			

Table 1: Radionuclides in common use

3.3 Environmental characteristics

Environmental conditions that may affect the investigation should be determined at an early stage.

It will be necessary to consider the effects of:

- building construction
- location (indoors or outdoors)
- background radiation levels
- temperature
- humidity
- light levels
- noise levels
- RF interference
- magnetic interference
- access
- radioactive contamination
- non-radiological hazards

The instrument selected to carry out the monitoring survey should perform adequately in the measurement environment.

3.4 Worker discussions

The initial assessment should ***always include a wide discussion with the workers in the area under investigation***. Senior staff should be approached to provide an overall picture of the work being carried out but the day to day working practices can only be fully determined by talking to the staff working in the area.

3.5 Records

Monitoring records must be kept.

It is a regulatory requirement that monitoring records are kept for at least two years.

Monitoring records should (as a minimum) list:

- instrument type
- instrument identifier
- instrument setup (including the use of end caps etc)
- working instructions
- monitoring procedure
- action levels
- measurement results
- the operator
- time and date of the measurements

When machine sources are monitored, such as X-ray sets, record the machine settings as well as dose rates produced.

Facilities should be made available for record keeping. These can range from simple forms to fully automated systems using data loggers and computers. Consider the benefits of providing a sketch of the areas to be monitored to the monitoring team. Mark the areas needing special attention. An example of a typical record sheet is shown in Section 3.5.1.

Valuable information can be obtained from the different records that have been kept for the area under investigation.

Historical records for the area should be available, which may establish whether changes in use of the area are significant – for example, an area around a linear accelerator may have produced activation products in the past, but the area may now only be used for sealed source work. The half life of the radionuclides used in previous work may also be relevant. Records of radioactive waste disposal from an area can be a useful source of information.

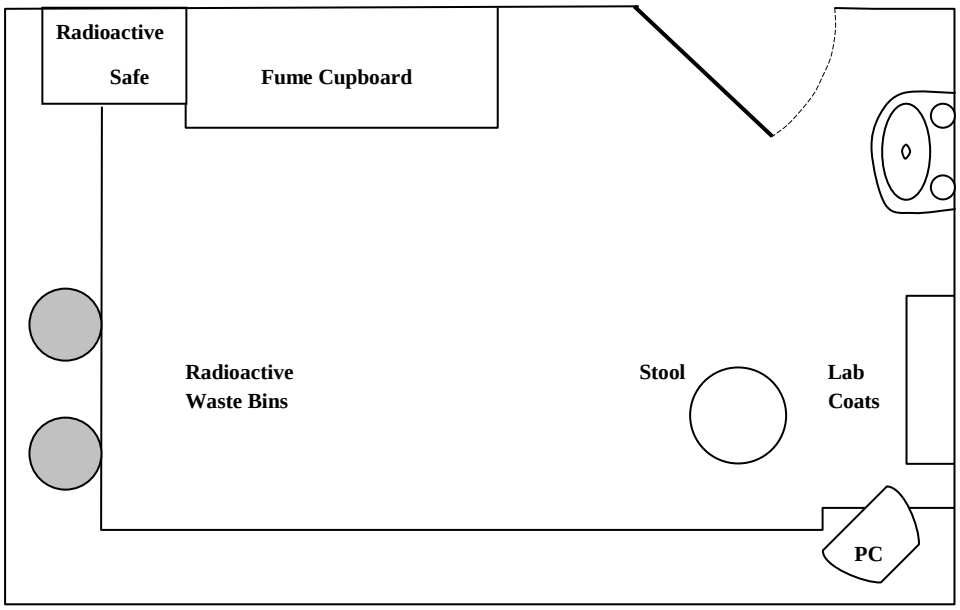
If no historical information is available, a worst case scenario must be assumed. In this case information will need to be gathered about the area through an initial or benchmark survey to assess dose rate and contamination levels before the monitoring strategy is established. The survey may include some or all of the following:

- dose rate checks
- monitoring of a/b/g contamination levels
- air sampling coupled with a/b/g spectrometry
- surface wipes coupled with a/b/g spectrometry
- liquid scintillation counting

The results from the initial or benchmark survey provide the basis for a monitoring strategy.

3.5.1 Typical record sheets

Room: *L12* **Building:** *6* **Instrument details:** *S/N 6398*



Other details: **Time:** *10:30 am*

Date: *01/03/2011*

Name: *S Davies*

Map of area

Room: *L12* Building: *6*

Location	Instrument type and I.D.	Action Level	Background Reading	Gross Reading
Fume Cupboard	S/N 101	100 cps (above bgd)	*50*	*60*
Radioactive Safe	S/N 101	100 cps	*60*	*85*
Sink	S/N 101	100 cps	*30*	*45*
Bench	S/N 682	100 cps	*20, 10*	*35, 15*
Radioactive Bins	S/N 101	100 cps	*40*	*90*
Floor	S/N 682	100 cps	*20, 10, 10*	*20, 15, 10*
PC	S/N 682	100 cps	*10*	*10*
Stool	S/N 682	100 cps	*10*	*10*
Lab Coats	S/N 682	100 cps	*10*	*10*
Handwash Basin	S/N 682	100 cps	*10*	*15*

Other details: **Time:** *10:30 am*

Name: *S Davies* **Date:** *01/03/2011*

4 Monitoring strategy

IN THIS CHAPTER

- Type of survey
- Selection of personnel
- Action levels
- Requirement for personal protective equipment (PPE)
- Monitoring approach
- Containment and barrier control
- Waste disposal
- Radiation protection instrumentation

When monitoring is necessary a strategy has to be developed in advance. This strategy will be influenced by the reason for the survey i.e. is it a routine measurement, or is it required due to an unusual or irregular occurrence?

This section lists the points that should be considered when devising an effective strategy in compliance with regulations[1], local rules and the principle of ALARP (keeping radiation exposure as low as reasonably practicable).

4.1 Type of Survey

The reason for the survey will influence the overall strategy. A survey can be described as benchmark, routine or non-routine. Techniques for performing these surveys are described in Section 6.

4.1.1 Benchmark survey

An initial or benchmark survey will need to be carried out to establish a level against which further surveys can be compared and confirm any historical information available. Only once all the available information has been gathered can the monitoring strategy be formulated and informed decisions made about personal protective equipment.

4.1.2 Routine Survey

A routine survey is usually performed in areas where radiological conditions are well known and generally consistent. Routine surveys can be associated with:

- Measurements within and at the boundary of areas to ensure they are correctly designated;
- Day-to-day duties to prevent the spread of contamination in an area or to personnel.

The results of surveys will usually be communicated through written survey reports. These may identify the need to perform a non-routine survey.

4.1.3 Non-routine Survey

A non-routine survey is usually associated with circumstances where the radiological conditions could be unknown, difficult to predict, or highly variable. Types of work associated with non-routine surveys are:

- Entry into areas where routine access is prohibited due to the radiological conditions;
- Maintenance activities that involve breaking into containment of equipment that processes radioactive substances (e.g. pumps, gloveboxes, compressors, gauges);
- Entry into an area to perform remediation work to restore adequate radiological controls;
- Accident or emergency situations.

This type of survey will usually involve interaction between the surveyor and other personnel (e.g. maintenance personnel). The surveyor may need to relay verbally current information about radiological conditions and simple radiological protection advice to a team or working party. A written survey report should be produced at the earliest opportunity after completion of the survey.

It will be necessary to specify the level of input required by the surveyor while any work is being performed:

- In circumstances where the level of intrusive works is minimal, and the levels of radiation and/or contamination are expected to be low, it may only be necessary to perform pre- and post- work surveys to confirm conditions have not changed due to the work;
- Where the level of intrusive works and radiological hazard is higher, it may be necessary to have a surveyor in continuous attendance. For example, a survey should be performed as each layer of shielding is removed or a layer of containment is breached. At other times the surveyor should stand back from the work, periodically monitoring the tools and personnel (e.g. gloves) for contamination;
- Where the radiological hazard could be high or unknown (e.g. entry into areas after an incident), slow, progressive monitoring is required. The surveyor should lead the team and ensure no person enters an area that has not yet been surveyed. Specialist instrumentation such as telescopic dose rate meters can maximise the distance between the surveyor and the potential hazard.

4.2 Selection of personnel

Personnel who carry out monitoring should be Suitably Qualified and Experienced Personnel (SQEP) and all work should be carried out under the supervision of trained radiation protection staff.

For a large operation in the UK the team may include:

- several surveyors
- surveyor supervisor
- radiation protection supervisor (RPS)
- radiation protection adviser (RPA)

For a small operation it may be necessary to train the individual performing the task to be an RPS.

4.3 Action Levels

Individuals performing monitoring must be briefed on what action to take should action levels be exceeded.

Action levels for dose rate and contamination (both surface and airborne) should be set in consultation with the responsible RPA.

Minimum recording dose rate and contamination action levels must be defined, above which records must be taken.

Maximum working dose rate and contamination action levels must be defined for the safety of personnel. If these levels are exceeded the surveyor should stop the work and seek advice.

The action levels should be set in accordance with ALARP and take into consideration any future use of the facility.

4.4 Requirement for personal protective equipment (PPE)

The specific methods of personal protection should be determined in consultation with the RPA.

The type of PPE required will depend upon the nature of the risk in a particular area. Where there is a risk of ingestion or inhalation due to loose contamination, PPE such as masks, gloves, aprons and coveralls may be necessary. For hospital X-ray departments where the risk is due to external radiation (diagnostic X-ray energy range 30-100 keV), coats, aprons and gloves with a suitable lead equivalence may be used. It may be appropriate to wear an active personal dosemeter while surveying.

4.5 Monitoring approach

It is critical that the degree and type of radiation or contamination is understood. Shielding of radiation or the containment of the contamination will be of fundamental importance.

4.5.1 Dose rate

To assess external dose rates, a walk around with a very sensitive detector, such as a sodium iodide scintillator, will identify:

- areas where the dose rate is essentially at background levels
- narrow beams
- hot spots

Particular care will be needed where poorly designed or damaged shielding on devices could give rise to highly collimated but intense beams of radiation (for example X-ray crystallography sets or industrial radiography sources). Beams from such equipment can increase general background radiation through scatter or 'sky shine' and can be difficult to detect. Careful consideration must be given when selecting instruments (see Section 5).

It may be necessary to revisit any areas producing high readings with more appropriate instruments.

Further detailed information on monitoring techniques can be found in Section 6.

4.5.2 Surface contamination

Large flat surfaces, such as work benches and floors, are obvious areas to begin the search for contamination, but vertical surfaces such as the walls above fume hoods should also be considered. Frequently touched areas (for example drawers, door handles and light switches) should also be examined. Where refurbishment is taking place, previously inaccessible areas may need to be monitored e.g. backs of cupboards, ducts, drains and filter banks.

The nature of the surface contamination will determine the monitoring strategy. If the area has been contaminated with an α emitter, low energy β emitter or X or low energy γ emitters, other factors will need to be considered. It is possible for the emissions to be absorbed in the surface; this is covered in more detail in Appendix 2.3. An example of such absorption would be where an area has been recently painted or refurbished, covering earlier contamination. Alpha and low energy β particles will not penetrate the new paint and will be essentially undetectable. A hazard may arise in the future if the paint should be disturbed. In this case, it may be necessary to strip all available surfaces in the area.

It should not be assumed that once an area has been assessed for radiation/contamination, it will remain in that state for ever – activity may diffuse out of surfaces, particularly those that have been wet.

Surface contamination can be described as either fixed or loose contamination. Further detailed information on monitoring techniques can be found in Section 6.

4.6 Containment and barrier control

In more serious situations, the assessment of the area to be monitored will indicate whether barrier controls are necessary. The type of barrier may vary from a line drawn across the floor, with a contamination monitor next to it, to a full changing room with washing facilities and portable monitors.

It may be necessary to seal the area from its surroundings with a PVC tent before starting operations.

4.7 Waste disposal

Identify disposal routes for all radioactive waste before commencing.

For a contamination clean up an adequate supply of the following will be needed:

- plastic bags
- waste bins
- sticky tape
- tissue wipes
- cleaning solvents
- instrumentation

A useful resource for information on waste disposal is the Environment Agencies' Requirements Working Group website[18].

4.8 Radiation protection instrumentation

All monitoring equipment should be tested and calibrated in accordance with the regulations[1]; suitable procedures for this are provided in other NPL Good Practice Guides. The scope of the calibration should cover all intended uses of the instrument.

The employer is responsible for the selection of the radiation protection instruments based on the recommendations of the RPA.

All instruments have strengths and weaknesses as illustrated in Appendix 1.

The RPA should be aware of the limitations of the different types of radiation protection instruments available.

Factors affecting the selection of radiation protection instrumentation include:

- The type of radiation/contamination present;
- The range to be measured;
- The environment in which the instrument is to be used. Can audio output and instrument alarms be heard clearly? Will the instrumentation work in high humidity?
- The availability of instruments (in-house or on loan);
- Availability of an instrument repair and calibration service;
- Access to laboratory counters and analytical equipment where sampling, such as air sampling, is to be carried out.

Further details on instrument selection can be found in Section 5.

If the probe selected is a ‘smart probe’ it may be calibrated separately from its ratemeter, otherwise a probe and ratemeter are calibrated as a pair and must always be used together as a pair.

Caution: many probes, in particular scintillation probes, can look almost identical but perform differently.

4.8.1 Pre-survey checks

Before the use of an instrument, consideration should be made to the:

- limitations of calibration
- mechanical condition
- battery condition
- cable and connector conditions
- background
- potential for surface contamination on the instrument itself
- response to a check source
- display digits (smooth operation) and backlight if provided
- analogue meter (free movement of needle)
- audio output
- condition of the detector window (e.g. light leaks)
- alarm setting
- mode of operation

Appropriate check sources, with sufficient output to produce a significant reading on all instruments used on a job, are extremely useful.

4.8.2 Post-survey checks

Following use of an instrument, consideration should be given to the:

- response to a check source
- potential damage during use
- potential contamination picked up on the instrument itself

5 Instrument types - making a choice

IN THIS CHAPTER

- X, γ and beta dose equivalent rate measurement
- Neutron dose equivalent rate monitoring
- Contamination monitoring

Instrument selection for radiation monitoring is not a trivial matter; the instrument must be matched to the radiation or radionuclides of instrument.

This section gives general guidance on the types of instruments that are available. A more extensive guide can be found in Appendix 1.

Generic aspects of importance include:

- Audio output. If there is any element of searching for the radiation, then an audio output is very useful. It gives an instant indication and allows the surveyor to concentrate on guiding the probe, rather than looking at the display;
- Sensitivity. Is the instrument capable of making meaningful measurements at the lowest decision level? This can be determined from the expected background count rate and the expected response to the radiation of interest. For example, for alpha contamination, the lowest useful count rate is approximately 4 s^{-1}. At this level, the chance of there being zero counts in any one second is low. Typically, when surveying for alpha contamination, each count is treated with suspicion. The surveyor will pause, and see whether there is a genuine elevated count rate or whether the click was one of the rare background events;
- Time constant. It is frustrating to have to wait a long time for an instrument indication to approach equilibrium when the dose rate etc has increased or decreased. For operational use, the time constant should not exceed about 4 seconds. This allows the surveyor to pause, wait about 12 seconds and then take an eye average over the following 10 seconds or so;
- Statistical fluctuation. This has to be balanced against the time constant. A short time constant will give a quick response but a high level of fluctuation. This makes it difficult to record an eye average. A long time constant will give a relatively fixed reading, but this demands that the surveyor waits a long time between readings and eye averages over a long period. For any monitoring process, 3 counts per second represents about the minimum level where both an acceptable time constant and an acceptable level of statistical fluctuation can be obtained. Note that achieving this balance is intrinsically more difficult with digital instruments. The best digital

instruments check whether the recorded count rate has genuinely changed or whether it could represent the same average level. If it appears to have changed, then the indication will move to the new value. If it does not, then it will be added into the average count rate calculation;

- The smallest source–detector distance anticipated. A simple rule in the measurement of dose rate is to try to work no closer than 3 times the maximum detector dimension from the source (due to the inverse square law). If using a Geiger Muller (GM) detector which is 50 mm in length, then reliable readings will be obtained down to a 150 mm source to detector centre distance. On the other hand, if the detector is a 400 cm^3 ionisation chamber, with a depth and width of about 80 mm, then the instrument will start to under-read for a source to detector centre distance less than 240 mm;
- The permitted averaging area. Any detector will average over its volume. If a large detector is exposed to a narrow radiation beam, the indication will be much lower than the dose rate in the beam. In most circumstances, it is impractical to use very small detectors where narrow beams are expected. The best that can usually be done is to choose a suitable detector and then define the averaging area as its area. This approach favours the use of GM tubes;
- Overload function. This is a potentially lethal problem with some instruments where the equipment has no protection against ‘fail to danger’ and the instrument reads zero in a high radiation field. It is absolutely essential that any instrument type, and preferably each instrument, has been tested up to the maximum intensity of radiation it could reasonably encounter. Fold back, or fail to danger at high dose rates, is unusual in any but the oldest European equipment, but can be a problem with USA and former Soviet Union GM instruments in particular.

Only use equipment with ‘fail to danger’ protection.

5.1 X, g and beta dose equivalent rate measurement

5.1.1 Geiger Muller detector

There are three varieties of Geiger Muller (GM) detector used for the measurement of ambient and directional dose equivalent rate from X, g and b sources:

- steel wall, energy compensated
  - typical minimum useful energy of 50 keV for X, g radiation
    - no useful b response
- thin end window, energy compensated
  - typical minimum useful energy of 10 keV for X, g radiation
  - no useful b response
- thin end window, uncompensated
  - response to X, g, and b sources

The advantages of the GM detector over the ionisation chamber are:

- The audio output, which makes it easier to find hot spots etc;
- The generally higher sensitivity. Where the aim is to measure dose rates at a few µSv per hour or less, ion chambers lack sensitivity. This means that they are slow to respond and have a high level of statistical fluctuation. In contrast, energy compensated 2 inch pancake GM detectors have a sensitivity of 5 counts per second per µSv per hour, which allows relatively quick measurement down to 1 µSv h^{-1};
- The compact detector, which allows measurement closer to sources.

The disadvantages are the slightly restricted polar (directional) response and the difficulties in interpreting readings in pulsed fields.

5.1.2 Ionisation chambers

Ionisation chambers are very popular instruments for routine monitoring. Provided that the radiation is incident generally from the front, an ionisation chamber is capable of measuring both ambient (slide closed) and directional (slide open) dose equivalent rate with sufficient accuracy from any energy of X, g or b radiation. It will also operate correctly in pulsed fields. Note that sensitivity is generally low and detectors are large.

5.1.3 Plastic scintillator detectors

In these instruments, a block of plastic scintillator material is coupled to a photomultiplier tube. Radiation energy deposited in the scintillator generates light. This is converted to an electric current by the photomultiplier tube and is then amplified. Because the scintillator has a mean atomic number close to that of tissue, these instruments reproduce the ambient dose equivalent fairly accurately. They are generally sensitive and are capable of making useful measurements below 1 μSv h^{-1}. They will also normally respond correctly to pulsed sources, but this should be confirmed. They are not, in general, useful for measuring β dose equivalent rate.

5.1.4 Sodium iodide based scintillation detectors

There is a class of instrument, generally termed 'Isotope Identifiers'. They use sodium iodide scintillators as low resolution gamma spectrometers and their main function is the identification of the radionuclides responsible for unexpected gamma radiation on the outside of vehicles and packages. Many of these also have an auxiliary dose rate function.

These instruments do not have an intrinsically good ambient dose equivalent rate response, but with modern electronics, the pulse spectrum can be processed using an algorithm to generate a reasonable dosimetric response over a useful energy range, typically 60 or 80 keV upwards. They have the enormous merit of high sensitivity allowing the measurement of dose rate down to close to background levels reasonably easily. The main constraint on their use is the relatively high minimum useful energy.

5.1.5 Dose rate measuring proportional counter

Instruments of this type are rare in the UK but they are available. They combine the best characteristics of the ionisation chamber (good energy and polar responses) with a detector that amplifies the signal and overcomes problems of measuring very low signal levels.

5.2 Neutron dose equivalent rate monitoring

An absorbed dose delivered by neutrons has a much higher radiobiological effectiveness than the same absorbed dose delivered by X or γ radiation. Monitoring neutron dose equivalent rate is made difficult by the extremely wide energy range that is routinely encountered (0.025 eV to 10 MeV or higher around high energy accelerators) and the fact that instruments do not have the correct dose equivalent response over this energy range. If the neutron spectrum is well characterised, it may be possible to select an instrument with a good response in the region where the majority of the dose equivalent occurs. Alternatively field specific correction factors based on the spectrum can be derived.

Various types of instrument exist, but all common units are based on detecting low energy (thermal) neutrons. A large mass of moderating material, normally polyethylene, surrounds the detector and is used to slow down the neutrons by collision. This, in combination with a thermal neutron absorbing layer, produces a tolerable energy response, but makes the instruments very heavy, typically 6 to 9 kg.

The common types are:

- BF_3 proportional counter, spherical moderator
- ^3He proportional counter, spherical moderator
- BF_3 proportional counter, cylindrical moderator
- LiI (Eu) scintillator, spherical moderator
- lightweight wide energy neutron scintillator

A detailed evaluation of moderator based neutron survey instruments is given in HPA-RPD-016[27].

5.3 Contamination monitoring

In most situations, the aim of monitoring is to identify the presence of contamination so that remedial action may be taken. Quantitative measurements to determine the activity on the surface (Bq cm^{-2}) can be difficult, as the readings depend on the radionuclide and the surface (see Appendix 2 for details).

For each of the three types of potential contaminant, a, b and X or g photon, there is a variety of types of instrument available.

5.3.1 Alpha contamination

Alpha emissions are characterised by their extremely short range (a few mm in air) and their very high rate of energy deposition. The monitors require very thin windows (approximately 1 mg cm^{-2}) to allow the particle to pass into the detecting volume but then have very high rates of energy deposition within the detector which can be used to give good discrimination against signals produced by b and X or g radiation. All alpha monitors should have a very low background, typically a few counts per minute. If the background is higher than normal, the probe is probably contaminated and should be cleaned before use or have the window replaced.

Typical detectors include:

- zinc sulphide scintillation detectors
- dual phosphor detectors
- thin window proportional counters

For scintillation types, it is important that they do not fail to danger if there is a light leak. This failure is common in older units, but modern units should alarm if there is a significant light leak. In the older units, a light leak can cause the instrument to fail completely with no sign other than a non-existent background count rate. As the background is very low, only a few counts per minute, it is easy for a user to fail to notice its absence and to carry on making measurements. All such measurements will indicate (possibly incorrectly) that the surface is clean. This failure is easy to detect automatically, and most modern ratemeters can be set up to do this. If a user is forced to use a ratemeter that does not alarm when a light leak occurs,

then it is important to perform a function check before and after a survey in case of damage during the survey.

5.3.2 Beta contamination

Beta contaminants found in practice range from ^{3}H (E_{max} = 0.018 MeV) to ^{106}Rh (E_{max} = 3.6 MeV). In the majority of circumstances, the lowest energies cannot be directly detected on a surface. ^{14}C (E_{max} = 0.156 MeV) is the lowest energy b emitter that is normally considered to be detectable but even this is challenging.

Typical detectors include:

- scintillation detectors
- refillable or sealed proportional counters
- thin end window or thin walled GM detectors

Light leaks in scintillation detectors will generally show up as an increase in background. Scintillation detectors should have a light leak detection mechanism to avoid any failure to danger.

5.3.3 Dual Alpha and Beta contamination probes

Some instruments are designed to respond to, and discriminate between, alpha and beta contamination. These instruments display alpha and beta count rates in separate channels. While the contribution of beta radiation to the alpha channel should be negligible, the alpha activity will normally contribute significantly to the beta channel count rate. Correct setting of the operating point is even more important for dual probes than for separate alpha and beta probes.

5.3.4 X, g contamination

Many radionuclides emit g radiation. This emission is normally preceded or accompanied by the emission of a b particle or other radiation. Contamination is normally monitored using the b emissions rather than the g radiation because b monitors have lower background count rates, higher detection efficiencies and a response that is far less influenced by activity not directly under the detector.

Examples of this decay pattern are:

- ^{137}Cs which decays by emission of a beta particle to ^{137m}Ba, a radionuclide with a 156 second half life that in turn decays with the generation of a 0.662 MeV g ray;
- ^{60}Co which emits both a relatively low energy b (0.31 MeV) and two energetic g rays (1.17 MeV and 1.33 MeV).

The only circumstance when the g emissions are normally used for the monitoring is when there is contamination in bulk; this situation will not be considered here.

There is, however, a large number of radionuclides which decay by electron capture and which emit low to medium energy X-rays. These radionuclides, including ^{55}Fe, ^{57}Co and ^{125}I, find frequent use in research and medical applications.

There are two popular types of detector for monitoring contamination by electron capture radionuclides:

- thin windowed sodium iodide scintillation detectors
- titanium windowed xenon filled proportional counters

Both types of detector have a good X and g detection efficiency but the lower energy threshold varies with window type and should be confirmed. The X-rays are only weakly attenuated by air, which means that monitoring can take place with the probe at a distance from the surface of interest.

The main problem tends to be the presence of other sources in the area, producing a high local background making the detection of contamination more difficult. One option is to use a detector which has a lead sleeve surrounding the scintillator. These are sometimes described as collimated detectors. Their use will reduce the background where the source of radiation is well off the axis of the detector, e.g. a source safe in a distant corner of the bench being monitored. The disadvantage of collimated detectors is that they are heavier.

6 Monitoring techniques

IN THIS CHAPTER

- Instrument reading techniques
- Measurement of dose rate
- Measurement of surface contamination
- Direct method

Guidance on monitoring techniques for both dose rate and contamination are given in this section.

There are a number of general points concerning monitoring using handheld portable radiation instruments that should be considered regardless of the radiation type that is to be measured:

- Ensure that the instrument is switched on for 2 to 3 minutes before going into the active area but note that ion chambers may require considerably longer;
- Try to ensure that the instrument has acclimatised to the ambient conditions; for example if the instrument is left in a cold area such as a vehicle overnight, it may not be at its correct operating temperature;
- It may not always be possible to fit the preferred instrument into some confined spaces. The use of separate probe and ratemeter instrument should be considered for some jobs;
- Place the instrument in the correct place, pointing in the correct direction, then if possible hold the instrument correctly and comfortably;
- Hold the instrument steady during the reading;
- Make sure the display can be seen and/or the audible signal can be heard.

6.1 Instrument reading techniques

There are two techniques that can be used to obtain an instrument reading: eye averaging and time integration. In both cases consideration must be given to understanding the meaning of the value displayed.

The displayed reading of some instruments may already have been integrated over a period of time and only visually updated intermittently. Some instruments have built-in integrating or averaging functions between display updates and updates may not be of a fixed frequency. Instrument response times vary and it is important to give the instrument time to respond to a changing radiation field. As a general rule of thumb, the total observation time should be a minimum of a few time constants.

Due to the randomness of radiation, an integrated measurement is usually more precise due to better statistics; this is particularly so when using digital or semi-digital display instruments that only display varying numbers or semi-analogue bar charts. However, similar levels of accuracy and precision may be achieved using the eye-averaging technique when using analogue instruments, provided there is a good match between the scaled display and the range of measurements to be made.

6.1.1 Eye averaging

An eye-averaged reading is obtained by the operator observing a fluctuating displayed reading and manually determining the average. There are two main techniques to eye averaging: systematic and intuitive (both techniques must be tempered with a degree of common sense to discount spurious/extreme readings).

- A systematic technique may be used whereby the result is taken to be the mean between the minimum and maximum of the observed readings over a period of time;
- An intuitive approach whereby the operator takes their perceived mean of the measurement readings over a period of time as the result.

Experience has shown that quite often the intuitive method can provide as good, if not better, results as the systematic approach. This is because most operators tend to be very good at eliminating outliers and make a weighted average of the low versus high readings which the systematic approach does not take into account.

It is important that the user is comfortable with the display characteristics of the instrument being used (e.g. with a log scale, the mid-point between the two marks is not the numerical mid-point value). If the pointer is not very close to the scale, care must be taken to avoid parallax errors, especially if the display is being viewed via a camera.

6.1.2 Integrating techniques

Most modern digital or semi-digital instruments provide an automatic integrated measurement function with a facility to vary the integration time. However it is also possible for the operator to perform a manual integration by recording the displayed reading over a chosen time period.

It is important to select the integration time taking account of :

- the expected radiation field
- the instrument response characteristics
- the required precision of the indicated reading

A long counting period will have a greater level of confidence than a shorter one. The statistical uncertainty of the indicated reading depends on the total number of counts

recorded. The more counts that can be recorded, the more reliable the measurement will be. As a general rule of thumb, the statistical uncertainty (at a coverage factor of *k=1*) of the reading is given by the square root of the number of counts recorded. So the percentage uncertainty is calculated as:

$$\frac{\sqrt{n}}{n} \quad x \quad 100\,\%$$

where n = number of counts measured.

For example, if 25 counts are measured, the uncertainty will be about 20 % from the counting statistics alone whereas if 250 counts are measured, the uncertainty will be around 6 %.

For a greater level of confidence, it is also advisable to make a number of integrated measurements.

6.2 Measurement of dose rate

Dose rate is measured separately for X, g, b and neutron radiation. It is important to recognise that different approaches are required for each situation.

6.2.1 Measurement of X and g dose rate

The operational quantity for the measurement of X, g dose rate defined from 10 keV upwards is the ambient dose equivalent H*(10). The guidance given below describes how to carry out a dose rate survey of an area for X, g dose rate measurements. The same principles also apply to the other radiation types but each requires the special considerations outlined in this section.

a) Perform a pre-survey instrument check (as in Section 4.8.1)

If there is the slightest suspicion about the instrument's condition, it should not be used.

b) Begin to monitor the area

Move cautiously through the area. The instrument should be set to the most appropriate range for the expected measurement. If the measurement is much higher than expected, retreat immediately. Carry out vertical and horizontal sweeps to ensure that no radiation beams or sources are missed.

IF IN DOUBT, MOVE AWAY!

There may be local requirements to measure at specified fixed points and orientations.

Points to consider

- Rapidly changing dose rate

  This is indicative of a localised source of radiation (‘hot spot’) or a narrow beam.

- Weak spots in shielding

  Concentrate on obvious weak spots such as doorways, cable ducts/penetrations and panel joins.

- Scattered radiation

  Radiation from the primary source may be scattered from objects, walls, floors and the ceiling. Scattered radiation has a lower energy than the primary radiation and can appear to emanate from locations away from the primary radiation source.

- Instrument interference

  Instruments may be susceptible to the effects of extreme environmental conditions or radio frequency interference.

- Unexpected dose rate pattern

  The RPA or RPS should be consulted if dose rate patterns are not as expected.

Take the specified action if the measured dose rates exceed the action levels set by the RPA (as determined when planning the monitoring strategy).

c) Record measurement results

It is important to record the results of measurements as they are made. The RPA will identify which results are to be recorded and how the records will be made.

d) Carry out post-survey instrument check

Immediately after completing the measurements, carry out a post-survey instrument check. If any of the checks indicate a problem, the survey may need to be repeated.

6.2.2 Measurement of beta dose rate

The operational quantity for the measurement of b dose rate, either on its own or in the presence of X, g radiation is directional dose equivalent, H¢(0.07). This is traditionally measured using an ion chamber instrument with the slide open but it can be estimated using a thin end window pancake GM detector, as they are small and shallow, which helps when working close to sources. Such instruments are generally scaled in counts per second. The indicated count rate should be divided by the response to ^{137}Cs gamma radiation in counts s^{-1} per µSv h^{-1} to give a conservative estimate of directional dose equivalent.

6.2.3 Measurement of neutron dose rate

Detection in neutron monitors is based on indirect methods where induced charged particles are measured and no information is available on the incident neutron energy. Neutron dose equivalent is difficult to measure precisely because of the very wide energy range over which measurements need to be made and the generally poor energy response of portable monitors. Knowledge of the neutron energy spectrum is needed for exact neutron dose rate measurement. However, instrumentation is available which will give an indication of neutron dose rate that is sufficiently accurate for radiation protection purposes under most circumstances.

Points to consider

Many neutron monitors are heavy due to the amount of moderating material required. Account should be taken of the ergonomics when selecting instruments.

6.3 Measurement of surface contamination

Determine whether contamination is fixed or loose

Fixed contamination is unlikely to cause an internal hazard unless the area undergoes abrasion resulting in re-suspension of the activity. It will only be an external radiation hazard where large quantities of beta- or gamma- emitting radionuclides have accumulated. If high readings are encountered using a beta or gamma contamination probe, it is advisable to either obtain a dose-rate measurement, or calculate the expected dose rate using instrument performance data. This will identify whether any further control or remediation measures are required.

Loose contamination presents an internal hazard. To minimize the spread of contamination and reduce the hazard to personnel, any loose contamination should be removed from the area. Any remaining contamination may be considered as fixed.

The type of contamination monitoring that could be used may involve measurements:

- by direct probe
- with dry wipes
- with damp wipes
- using all three methods

6.3.1 Direct method

Direct contamination monitoring may provide a reasonable assessment of the contamination level, subject to the caveats given later in this section, but for more accurate measurements there may be a need to take samples of the surface for laboratory analysis (this is beyond the scope of this Guide).

Normally, the most efficient way of detecting contamination is by listening to the audio output of the monitor. The user should concentrate on moving the detector over the surface of interest at the appropriate probe to surface spacing and speed.

This is important because the majority of contamination detectors are extremely fragile and the surface-to-probe spacing can be critical.

Perform a pre-survey instrument check (as in Section 4.8.1)

If there is the slightest suspicion about the instrument's condition, it should not be used.

Points to consider:

- Nature and location of the contamination

The measurement will be affected by the following:

- § surface absorbency
- § presence of water/grease/dirt/paint/polish on the surface
- § type and energy of radiation
- § time constant of instrument
- § distribution of potential contamination
- § other radiation sources in the vicinity. There may be a need to remove sources or shield an area before the contamination monitoring is started.

See Appendix 2 for examples of how these will affect the instrument reading.

- The averaging area

For body measurements, contamination should be averaged over an area of 300 cm^2 or less, except when doses to skin are being assessed when the averaging area is then $1cm^2$.

For other surfaces, contamination should be averaged over an area of 1000 cm^2 or less.

- The detector to surface distance of measurements

  Alpha and low energy b emissions will only be detected if the probe to surface distance is not greater than a few millimetres. Where this is impossible to achieve because the surface is uneven, consider other options such as dry or wet wipes. Wipe testing is covered in Section 6.3.

Where the expected contaminant has a low range, the probe must be held close to the surface being monitored – a distance of 3 mm is standard but is difficult to achieve with any accuracy. **Never let the probe touch the surface as this might cause it to become contaminated.**

For reasonably energetic betas, X and γ rays, where contamination is expected to be low, one practical solution to the problem is to use a spacer or gloved finger to regulate the distance of the probe from the surface, providing the area is smooth. Hold the probe so that one gloved finger at the **trailing edge of the probe** touches the surface, supporting the probe at about 10 mm above it. The probe is then moved over the area of interest but always with the supporting finger trailing so that it only touches areas of the surface that have already been monitored. Take care not to touch any surfaces that are obviously contaminated. Check regularly that contamination is not building up on the glove. This method would not be possible if attempting to measure alpha contamination due to its low range.

The monitoring distance can be increased for a contaminant of energetic b particles or X or g rays. The practical effect of this is to increase the averaging area.

- Speed of monitoring

  The speed at which an area can be monitored is discussed in Appendix 4 but once contamination has been located, a more accurate assessment should be made with a static measurement.

- Skin/clothing material being monitored

  Care should be taken when attempting to assess a or low energy b contamination as complete absorption of the radiation could occur in the top few layers of skin or within the fibres of a material; the absorption rate is affected by particle size and clothing material. These issues are described in more detail in Appendix 2.

- Recording measurements
  - all relevant measurements required by the RPA or RPS should be recorded

- § if short-lived radionuclides are being measured, the time of measurement will also be important
- § if decontamination is carried out or contamination removed, it may be necessary to provide pre- and post- monitoring results

· Staff who carry out monitoring must be aware of the action levels determined for each area and know what to do if these levels are exceeded (as established when planning the monitoring strategy).

Before leaving the area

When leaving the contamination area remove any protective clothing and monitor yourself in accordance with local rules.

Carry out post-survey instrument check

Immediately after completing the measurement carry out post-survey checks. If any of the checks indicate a problem, the survey may need to be repeated.

6.3.2 Indirect measurement of surface contamination (wipe testing)

Wipe tests can be either ‘Dry wipe’ or ‘Wet wipe’. In general it will be a senior health physics professional who will make the decision on which to use. Purely fixed contamination will not be detected using a wipe method.

A typical wipe test procedure uses a filter paper firmly wiped over an area of 100 to 1000 cm^2 of a surface that may be contaminated with radioactivity. The filter paper can either be placed in an alpha/beta drawer counter to assess the level and type of activity, or sent to a radio-chemistry laboratory for a full assessment of radionuclide type and activity. In both instances, all measurements should be traceable to national standards.

The uncertainties in assessing the levels of contamination from wipe tests are high. The wipe efficiency, i.e. the percentage of contamination picked up by a single swipe of the surface (‘Pick-up’ factor), is affected by many factors including, but not limited to:

- · the type of wipe used
- · the pressure applied by the person when making the wipe
- · the area wiped
- · the contamination distribution
- · the porosity, chemical composition, texture and cleanliness of the surface

‘Pick-up’ factors can vary enormously and are almost impossible to assess accurately and the uncertainties in the ‘Pick-up’ factor are an order of magnitude larger than other uncertainties in the measurement. Consequently it has been common practice to allocate a value of 10 % to the ‘Pick-up’ factor, as essentially a ‘Best Guess’.

7 Interpretation of results

IN THIS CHAPTER

- Quantities and units of measurement
- Instrument calibration
- Problem areas in interpretation of results
- Uncertainties in measurement

Once a survey has been completed, the meaning of the results obtained must be correctly interpreted. This is usually the responsibility of the RPA, on behalf of the employer, but may be undertaken by the qualified person.

7.1 Quantities and units of measurement

To interpret the measurements, there is a need to understand radiological units. Here we indicate the most common units in which radiological instruments are scaled.

7.1.1 Dose / dose rate

It is not possible to directly, and physically, measure the actual amount of energy deposited (i.e. doses) in the organs of people. Therefore alternative operational dose quantities are used by international convention to provide best and accepted estimates.

It is good practice to measure doses to personnel with a personal dosemeter but an alternative method is to estimate the effective dose with a hand held monitoring instrument.

The convention in radiation protection for area monitoring is to use:

- Ambient dose equivalent for the control of effective dose to people, e.g. to define a designated area as ‘Controlled’ or ‘Supervised’;
- Directional dose equivalent for the control of doses to the skin and the lens of the eye.

Ambient dose equivalent, H*(d), is the normal monitoring quantity for X, gamma and neutron radiation where d is the depth in tissue at which the dose rate applies. It is designed to give an upper estimate of effective dose for external irradiation of the body for the vast majority of circumstances. Its other merit is that a measurement of ambient dose equivalent at a point will normally give the maximum possible $H_p(10)$ personal dose equivalent rate, i.e. the dose rate monitored by a personal dosemeter. The international convention in radiation protection is to use the ambient dose equivalent at 10 mm depth i.e. H*(10).

Directional dose equivalent, H¢(d) is intended for use with less penetrating radiations where the dose rate drops off quickly in 10 mm of soft tissue. Its main use is for skin dose at a depth of 0.07 mm, but it is also used for dose to the lens of the eye at 3 mm. This directional dose equivalent is not an isotropic quantity i.e. the monitor is expected to be pointed at something which is the cause of the exposure. Note that energetic X and gamma radiation will also contribute to H¢(0.07) and H¢(10) but the value will be similar to H*(10). Hence we do not usually measure it separately when dealing with penetrating radiations.

The operational quantities that should be measured using portable instruments during dose rate surveys are therefore:

- ambient dose equivalent at 10 mm depth, H*(10) - SI unit: sievert (Sv)
- ambient dose equivalent rate, H*(10) h^{-1} - SI unit: sievert per hour (Sv h^{-1})
- directional dose equivalent at 0.07 mm depth, H(0.07) - SI unit: sievert (Sv)
- directional dose equivalent rate, H(0.07) h^{-1} - SI unit: sievert per hour (Sv h^{-1})

Alternatively some instruments may measure other quantities which enable conversion to the desired dose quantity to be assessed using ICRU57[16] or ICRP74[12] dose conversion coefficients for each energy contribution. However, use of those conversion coefficients require a detailed understanding of the radiation field being measured which is often impractical. This can lead to much larger errors than estimates based on H*(10) alone. The alternative quantities measured may be:

- fluence rate (usually read in counts per second)
- air kerma rate (Gy h^{-1})
- absorbed dose rate in air (Gy h^{-1})

Very old instruments, and many manufactured for use in the USA, still use exposure rate in roentgen per hour as the measurement quantity for X and gamma radiation. These instruments should, if possible, be re-scaled and have their detectors modified to measure the desired quantities. If this is difficult, an approximation for energetic X and gamma radiation can be made using a conversion factor of 100 R = 1 Sv.

Estimation of dose is a specialist task when using instruments not scaled in dose equivalent or dose equivalent rate. For example, the conversion coefficient from air kerma to ambient dose equivalent[16] varies as shown in Figure 1. For some common energies the conversion coefficient is as follows:

- 1.15 Sv Gy^{-1} for ^{60}Co at 1.25 MeV
- 1.20 Sv Gy^{-1} for ^{137}Cs at 662 keV
- 1.74 Sv Gy^{-1} for ^{241}Am at 60 keV

In most circumstances, insufficient information is known about the radiation field to make this conversion accurately, except under the following restricted conditions:

- Where the instrument is located in a scatter free radiation field and the photon energies are known;
- Where the source or X-ray spectrum is well attenuated by shielding and the radiation reaching the detector can be presumed to be the highest energy generated e.g. X-rays emerging from the housing of a 30 kVp X-ray tube can be taken to be 30 keV.

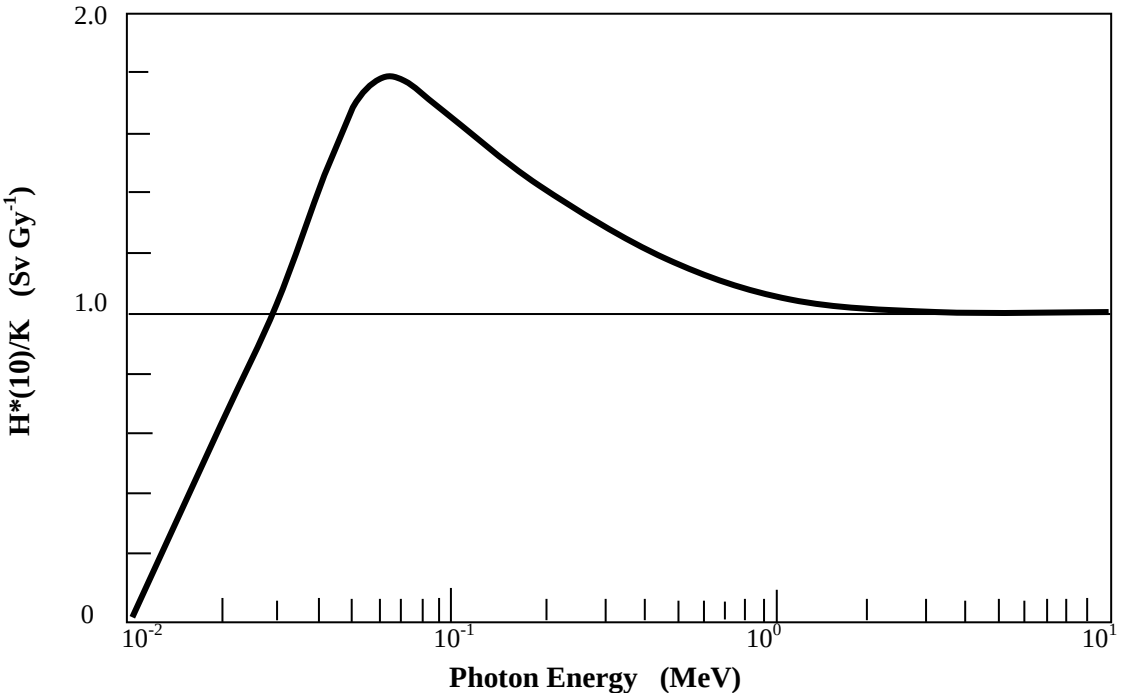


Figure 1: Conversion factor from air kerma to ambient dose equivalent

7.1.2 Contamination

The units most commonly found on instruments used for contamination monitoring are:

- counts per second (cs^{-1}, cps, ps^{-1} and s^{-1})
- disintegrations per minute (dpm)
- becquerel (Bq)
- becquerels per square centimetre (Bq cm^{-2})

If the instrument indicates ‘becquerels’, or ‘becquerels per square centimetre’, a calibration factor will have been stored in the instrument. Conversion of counts per second to becquerels or becquerels per square centimetre can be complicated. This task requires a comprehensive knowledge of decay schemes, instrument performance and some estimation of how the local conditions (e.g. surface construction) might affect the observed count rate. Methods for this conversion are discussed in Appendix 2.

The RPA should be consulted to provide guidance on the validity of any stored calibration factors.

7.2 Instrument calibration

It is a statutory requirement[1] that all instruments used for the monitoring of controlled or supervised areas are tested on a regular basis.

Instrument testing and calibration should be carried out in accordance with GPG14[3] and GPG29[4]. A calibration will determine the instrument's response to a range of well-defined radiations under reference conditions. This provides the user with evidence that the instrument's response is satisfactory. It will usually confirm whether the response curve provided in the manual or type test data is satisfactory for use.

Any limitations of either the calibration procedure or the performance of an instrument must be clearly stated on the certificate.

7.2.1 Dose / dose rate

The instrument should be calibrated in terms of Ambient Dose Equivalent. The results of calibration may be stated as the instrument response (I_R) in terms of ambient dose equivalent H*(10) for ^{137}Cs, where:

$$I_R = \frac{(R_i - B)}{H^*(10)}$$

and

R_i = observed dose (Sv)

B = background dose (Sv)

H*(10) = applied ^{137}Cs ambient dose equivalent (Sv)

Alternatively, the quantities used may be expressed as dose rates (Sv h^{-1}) in place of dose in the above formula.

For example, if the applied ^{137}Cs ambient dose equivalent rate is 500 µSv h^{-1}, the observed dose rate is 551 µSv h^{-1} and the background dose rate is 1 µSv h^{-1}, the instrument response (I_R) is 1.10 (i.e. the observed response of the instrument should be divided by 1.10 to obtain the H*(10) ambient dose equivalent rate). The calibration may also be stated in terms of the calibration factor (Cf), which is the reciprocal of the instrument response. In the example above, the calibration factor would be 0.91 and the instrument reading should be multiplied by this factor to obtain the H*(10) ambient dose equivalent rate.

Similar calibration data will usually be obtained using ^{241}Am (60 keV) and ^{60}Co (average 1.25 MeV).

In most operational circumstances, instruments are chosen with responses (and hence also the calibration factors) close to unity. No correction for the instrument calibration is normally necessary, as other factors such as the energy spectrum also affect the instrument response. Most instruments in common use will have a relatively flat energy response between 60 keV and 1500 keV. If it is known that the instrument will be used to measure energies beyond

these, it will be necessary to consult the energy response curve of the instrument provided in the manufacturer's data and make suitable corrections. There may also be a need to interpret the calibration data and manufacturer's type test data if the instrument is to be used as a transfer standard or if the results have legal implications. Guidance on interpreting manufacturer's type test data can be found in Appendix 3.

7.2.2 Contamination

The readings on a surface contamination monitor require interpretation to obtain the quantity of interest (Bq cm^{-2}) (see Appendix 2). The calibration certificate records the instrument's response to a range of ISO reference sources at a specified distance. The ISO reference sources[5] are specialist sources produced for the purpose of calibration, they are sometimes modified by filters and should not be considered as realistic sources of a particular radionuclide. They are designed to provide calibration laboratories with a consistent, reproducible method of determining a detector's response to a range of radiation types and energies. The traceable quantity of a reference source is the surface emission rate per unit area (SER) which is the number of particles or photons emitted from each cm^2 of the surface of the source per second.

The results of a calibration of a surface contamination monitor may be quoted on a certificate in various ways:

- Instrument response - counts per second per emission per unit area of the calibration source ($I_R(E)$);
- Calibration factor - the inverse of the instrument response;
- 2π detector efficiency - the probability of detecting an emission from the source directly under the detector window, expressed as a percentage;
- Instrument response - counts per second per Bq per unit area of the calibration source ($I_R(A)$).

If we define:

R_i = reading (counts per second) with the source present

B = background reading (counts per second) with the source removed

SER = the surface emission rate per unit area of the source (α, β or photons s^{-1} cm^{-2}), taken from the source calibration certificate

A = area (cm^2) of the probe window, from manufacturer's specification

P = ratio of the activity (Bq cm^{-2}) to the emission rate (α, β or photons s^{-1} cm^{-2}) for the reference source (so-called 'P-factor')

then the quantities defined in this section are given by:

$$IR(E) = \frac{R_i - B}{SER}$$

$$CF_E = \frac{SER}{R_i - B}$$

$$2\pi \text{ eff} = 100 \times \frac{R_i - B}{SER \times A}$$

$$IR(A) = \frac{R_i - B}{SER \times P}$$

As an example, suppose an instrument reads 90 counts per second when exposed to a ^{36}Cl source with a certificated emission rate of 25 betas s^{-1} cm^{-2}, the background count rate is 10 counts per second and the probe area is 10 cm^2:

$IR(E) = 3.2\ s^{-1} / (\beta\ s^{-1}\ cm\text{-}^{2})$

$CF_E = 0.31\ \beta\ s^{-1}\ cm^{-2} / s^{-1}$

2π eff = 32 %

For an ‘ideal’ ^{36}Cl reference source, the activity is double the emission rate, as one beta particle is emitted per decay but only 50 % of these are emitted from the surface. The ‘P-factor’ in this case is 2, and:

$I_R(A) = 1.6\ s^{-1}\ Bq^{-1}\ cm^2$

Further details of the P-factor and issues in interpreting readings on surface contamination instruments are given in Appendix 2.

7.3 Problem areas in interpretation of results

In this section the potential for incorrect assessments is highlighted.

7.3.1 Dose rate

Close approach to sources

As a general rule when measuring dose rate from a point source, the detector should not be placed closer than three times the detector dimensions because the radiation field is no longer uniform. A closer approach will lead to an increasing underestimate of the dose rate. Measurements can be made at greater distances and corrected for the inverse square law.

For a small area b emitting source it may be necessary to measure at a closer distance in order to detect it, but the user should be aware that there can be gross underestimates because the dose rate in contact with the source could be 100 times greater than the measured instrument indication when using a typical ion chamber instrument that has a large detector volume. An extremity dosemeter placed in close proximity to the source may provide more reliable measurements.

Dead time

Most commercial instruments for the measurement of dose rate will have built in dead time corrections. However, there are some instruments in the field that do not automatically compensate for dead time, guidance on how to correct an instrument reading to account for losses due to dead time is provided in Appendix 7.

Consult the instrument manual to confirm whether manual dead time correction is required.

Pulsed sources generating narrow pulses with durations less than 30 ms

The use of pulse measuring equipment is not recommended in pulsed radiation fields, for example, from Linacs. The pulse from the machine is commonly only a few µs long, which means the instrument can only record one count, no matter how intense the dose rate. It is safer to use instrumentation that measures the intensity of each pulse rather than simply detecting it or not, e.g. ion chamber instruments or passive dosemeters.

Measuring pulsed radiation sources is a specialised task.

The problem with such an approach is that ionisation chambers do not work well at low dose rates and passive dosemeters cannot be used to search for shielding weaknesses. Hence it may be necessary to use a pulse measuring instrument but expert advice should be sought to interpret the readings.

As an example, consider a pulsed X-ray machine producing 5 ms wide pulses at 200 Hz. At the limit, a GM counter will produce 200 counts per second. If the detector is a sensitive type, with a calibrated response of 5 counts per second per mSv per hour, at its limit the indicated dose rate will be (200/5) = 40 mSv h^{-1}. However, in reality the actual dose rate could be of the order of 1 Sv h^{-1}. The instrument will be generally trustworthy where the chance of detecting each machine pulse is less than 30 %. For the instrument above, this would be 30 % of 200 s^{-1} = 66 s^{-1}, corresponding to a maximum trustworthy indication of about 13 µSv h^{-1}.

Scattered and transmitted spectra

Shielding a radiation source reduces the intensity but also changes the energy spectrum, affecting instrument response.

X-ray equipment will produce a range of energies up to the maximum energy that is generated by the peak voltage on the tube. The lowest energies are attenuated by the tube casing and shielding, so the mean energy increases (the beam is hardened) and on the outside of intact shielding it is a valid assumption that the mean energy of the transmitted beam in keV is close to the tube voltage in kV. A similar process also takes place with g sources.

If radiation is scattered through a maze entrance, or by the air above a source room with thick walls and a thin roof, then the mean energy of the radiation reaching a worker is reduced. As an example, a ^{60}Co g emitting source (mean energy 1.25 MeV) in a room with a maze entrance and without a heavy door could produce a mean energy at the door of 150 keV [17].

For instruments that read in dosimetric quantities it is not necessary to correct for these effects providing that the instrument has a good energy response and there is no significant component below the useful working energy range. However for other instruments the combination of these effects makes it very difficult to calculate a correction factor.

7.3.2 Contamination

There are many problem areas when attempting to interpret a contamination measurement. Some of the more important are:

- Surface–detector distances because close monitoring may be required;
- Dead time. If the correction is not built into an instrument's scale, it can be accounted for. See Appendix 7;
- Instrument detection efficiency. This may be complicated, especially if multiple emissions occur. See Appendix 2;
- Absorption of radiation by surface coverings (e.g. paint, grease). In some instances the effect of a coat of paint may be that the contamination is not detectable at all. See Appendix 2.

Precise measurements are rarely required and providing rational assumptions are made and realistic uncertainties are determined, contamination monitors and wipe test techniques can be used to provide estimates of activity levels present. Guidance on the specialist task of estimating surface activity can be found in Appendix 2 (single radionuclide) and Appendix 6 (mixed radionuclides).

7.4 Uncertainties in measurement

Every measurement has an uncertainty associated with it. This will be made up of the uncertainty in the calibration factor, or instrument response, of the instrument and the uncertainty in the measurement made using the instrument. Generally the uncertainty in the instrument calibration factor will be assessed by a specialist test house using well-defined sources and measurement facilities and the uncertainty on the calibration factors may be as small as a few percent. However the monitoring process is very much less well-defined and the associated uncertainties are usually at least one order of magnitude greater than the calibration factor uncertainty and may often be much larger. The uncertainty for a radiation survey or contamination survey result needs to include the uncertainty in the instrument calibration factor AND the uncertainty arising from the monitoring process. Guidance follows on common components that need to be considered.

7.4.1 Assessment of uncertainty in a measurement

For any measurement there will be a statistical uncertainty. A surveyor is likely to get an appreciation of this uncertainty by repeated use of the instrument. In addition to this, the following sources of uncertainty may need to be considered.

For dose rate monitors the most likely deviations from calibration conditions may be:

- The energy of the incident radiation is frequently unknown, due to scatter and absorption. As a consequence of this, the uncertainty of the response of the instrument can be up to ±30 %;
- The directional distribution of the radiation field;
- The uniformity of the radiation field;
- For vented ion chambers, pressure & temperature effects (unless accounted and corrected for).

Additional uncertainties associated with the measurement may be:

- Statistical variation of the observed reading;
- Dead time;
- Area over which the measurement is averaged;
- Variation in radiation background level.

For contamination monitors the most likely deviations from calibration conditions will be due to:

- The energy of the incident radiation. This is unlikely to be mono-energetic or of the same energy as the calibration energy;
- The condition of the contaminated surface. The type of surface, the amounts of dust, grease and grime covering or mixed in with the contaminant, the extent of the contaminated area and the geometry of the surface;
- The distance of the detector or probe from the contaminated surface;
- The speed of monitoring, i.e. how fast the detector was moved over the surface being monitored;
- The distribution of contamination, i.e. whether the contaminant is distributed as random hot spots or is uniformly spread across the surface;
- The direction of the radiations emitted.

For a wipe test measurement, uncertainties will be due to:

- The type of wipe used;
- The pressure applied by the person when making the wipe;
- The area wiped;
- The contamination distribution;
- The porosity, chemical composition, texture and cleanliness of the surface.

The amount that a wipe removes or the ‘Pick-up’ factor can vary enormously and is almost impossible to assess accurately[15]. The uncertainties in the Pick-up factor are an order of magnitude larger than other uncertainties in the measurement. Consequently it has been common practice within the industry to allocate a value of 10 % to the Pick-up factor as essentially a ‘Best Guess’ and is generally conservative.

In any measurement scenario, a record should be kept of which factors have been considered that contribute to the uncertainty along with any assumptions made.

A significant quantity of detailed guidance on uncertainties generally, and on ionizing radiation measurements in particular, is available[24,25,26].

Appendix 1 Detector characteristics

A1.1 X, g, b dose equivalent rate measurement

DETECTOR TYPE	STRENGTHS	WEAKNESSES
IONISATION CHAMBER	· Can have very good X, g energy and polar response and acceptable b characteristics. · No problems with pulsed fields. · Generally good dynamic range of dose rates, typically 2 mSv h^{-1} to 10 mSv h^{-1} but on other types 2 mSv h^{-1} to 10 Sv h^{-1}.	· Very low signal level at normal radiation protection dose rates leading to poor statistical fluctuation or slow response times. · Generally unusable below 2 mSv h^{-1}. · Susceptible to temperature and humidity problems. · Requires good maintenance, particularly regular drying of desiccant. · Often use unusual polarising batteries. · Generally no audio output.
DOSE RATE MEASURING PROPORTIONAL COUNTER	· Good X, g energy response down to ~ 30 keV. · Useful beta response at higher energies. · Generally satisfactory with pulsed fields. · Good sensitivity for detector size. · Wide dynamic range of usable dose rates. Low dose rates often use high gain (high detector polarising voltage) and high dose rates a lower voltage and hence lower gain. · Sometimes an audio output.	· Relatively vulnerable detector in the b versions. · Can use very high polarising voltages. · Expensive. · Susceptible to high voltage variation.
STEEL WALLED ENERGY COMPENSATED GM	· Very easy to process signal. · Much more sensitive than an ion chamber. As an example, a GM with a volume of 10 cm^3 will produce as stable an indication on the meter as an ion chamber of 300 cm^3. · Consistent. The operating voltage is fixed and the sensitivity on the larger ones varies little. · Stable and long lived, if undamaged. · Low cost. · Audio output.	· No useful b response and an X, g response that falls rapidly below ~ 50 keV. · Problems in pulsed fields. Untrustworthy when the count rate from the detector exceeds about 35 % of the pulse rate from a machine producing narrow (ms) pulses. Ultimately, in the main beam, perhaps at 1 Sv h^{-1}, the detector will respond to each pulse, not to the dose rate. This will lead to a potentially serious under-response.
THIN END WINDOW, ENERGY COMPENSATED GM	· Acceptable X, g energy response from 10 or 15 keV upwards to 1.25 MeV. · Good polar response.	· Instruments where the filter can be removed so that the detector can be used as a conventional end window detector are susceptible to damage.
END WINDOW GM DETECTORS	· Respond to X, g radiations from 5 keV upwards and to all b radiation which contributes to ambient or directional dose equivalent rate. · Acceptable response (pancake types).	· If used with the window unprotected, i.e. for b and very low energy X, g measurements, they are very vulnerable to damage. Damage to the window generally cannot be repaired. They must be protected with a fine etched metal or plastic grill. · Poor energy response for X, g radiation.
PLASTIC SCINTILLATOR BASED INSTRUMENTS	· Good X, g energy and polar response for ambient dose equivalent rate down to 20 keV for instruments with smaller scintillators and thin cans. · High sensitivity. A 50 mm x 50 mm plastic scintillator will operate reasonably well at background levels. · Good dynamic range. In the same way as the proportional counter they can be operated at high voltage (hence high gain) at low dose rates and lower voltage (hence low gain) at high rates. · Easy to produce a logarithmic dose rate response.	· Large detector (scintillator and photomultiplier tube). · Expensive. · Generally no audio output.
SODIUM IODIDE BASED SCINTILLATION DETECTORS	· Very high sensitivity. · Radionuclide identification. · Generally an audio output.	· Very expensive. · Limited dynamic range.

A1.2 Neutron dose equivalent rate monitoring

DETECTOR TYPE	STRENGTHS	WEAKNESSES
BF_3 PROPORTIONAL COUNTER, SPHERICAL MODERATOR	· Near isotropic response. · Good γ rejection.	· BF_3 is poisonous.
^3He PROPORTIONAL COUNTER, SPHERICAL MODERATOR	· Near isotropic response.	· ^3He is expensive.
BF_3 PROPORTIONAL COUNTER, CYLINDRICAL MODERATOR	· Good γ rejection.	· Non isotropic response. · BF_3 is poisonous.
LiI(Eu) SCINTILLATOR, SPHERICAL MODERATOR	· Near isotropic response.	· Poor sensitivity, typically 0.2 s^{-1} mSv^{-1}h. · An energy response inferior to the cylindrical form. · Poor γ rejection. · Variable operating voltage.
LIGHTWEIGHT WIDE ENERGY NEUTRON SCINTILLATOR	· Lightweight. · High sensitivity.	· Limited gamma rejection.

A1.3 Alpha contamination monitoring

DETECTOR TYPE	STRENGTHS	WEAKNESSES
ZINC SULPHIDE SCINTILLATION DETECTORS	· Good detection efficiency. The majority of a particles that penetrate the window with significant energy will be counted. · Available in a wide range of sizes. · Reasonable b and X and g rejection although ultimately either false counts will be recorded at high dose rates or the detector will fail to danger. · Light weight. Most instruments use separate probes. · Low intrinsic background. · Easy setting up procedure.	· Sensitive to high magnetic fields, unless filled with a mu metal screen. · The uniformity of the larger detectors can be poor, with a low response to activity in the detector corners. · Very variable optimum operating voltage, normally between 700 and 1200 V.
DUAL PHOSPHOR SCINTILLATION PROBES (ZINC SULPHIDE ON PLASTIC SCINTILLATOR)	· Good a detection efficiency for standard a pulses. · Useful for mixed a and medium to high energy b contamination. · Light weight. · Easy window repair.	· More complicated setting up procedure, which is also more demanding on the ratemeter. · Sensitive to high magnetic fields, unless filled with a mu metal screen. · Very variable operating voltage.
THIN WINDOWED, GAS REFILLABLE PROPORTIONAL COUNTERS	· Very good detection efficiency. Virtually any a particle passing through the window with an energy in excess of 0.5 MeV will be counted. · Available in very large sizes, if required. · Also good b detection efficiency, operating well down to 0.156 MeV for ^{14}C. · Easy window repair. · Consistent operating potential. · Not influenced by magnetic fields.	· Require regular refreshing with counting gas. · They are not suitable for intermittent use. · Operation at very high voltages (1.5 to 2 kV) may cause problems in high humidity.

A1.4 Beta contamination monitoring

DETECTOR TYPE	STRENGTHS	WEAKNESSES
BETA SCINTILLATION DETECTORS	· Available in a wide range of sizes. · Can cover a wide range of energies. · Inefficient response to lower energy X, g radiation, helping to minimise background. · Window easily replaced. · Light weight. · Easy setting up procedure.	· Susceptible to magnetic interference. · Very variable operating potential within any one type. · Uniformity of larger detectors can be poor. · No alpha discrimination unless in 'dual phosphor probe' form.
THIN WINDOWED, GAS REFILLABLE PROPORTIONAL COUNTERS	· Very good detection efficiency. · Available in very large sizes, if required. · A very good b detection efficiency, operating well down to 0.156 MeV for ^{14}C. · Easy window repair. · Consistent operating potential. · Not influenced by magnetic fields. · Good a rejection.	· Require regular refreshing with counting gas. · They are not suitable for intermittent use. · Operate at very high voltages (1.5 to 2 kV).
TITANIUM WINDOWED, XENON FILLED SEALED PROPORTIONAL COUNTERS	· Useful for b and low energy X and g radiation. · Relatively tough window. · Light weight. · No gas filling required. · Consistent operating potential and radiation characteristics.	· Window not easily replaced. Repair/exchange costs can be expensive. · Higher background than all other types per unit area.
THIN END WINDOW GEIGER MULLER DETECTORS	· Large, easily processed pulse. · Very simple setting up procedure. · Consistent operating voltage and radiation characteristics. · Lowest cost overall option in most circumstances. · Light and compact.	· Windows are extremely vulnerable and cannot be repaired. · Not available in large sizes.
THIN WALLED GEIGER MULLER DETECTORS	· More robust than the thin window variety. · Larger useful area than the thin window variety. · Very simple setting up procedure. · Consistent operating voltage and radiation characteristics. · Low cost. · Light weight.	· Relatively high minimum useful energy. · Unrepairable.

A1.5 X, γ contamination monitoring

DETECTOR TYPE	STRENGTHS	WEAKNESSES
THIN WINDOWED, THIN SODIUM IODIDE SCINTILLATOR	· The thin crystal is a very efficient X, γ photon detector. For the 3 mm thickness the detection probability is greater than 0.5 for normal incident radiation up to 120 keV. · A typical aluminium window, 14 mg cm^{-2} thick has a transmission of at least 0.8 for normal incident X, γ photon radiation down to 10 keV. For a typical beryllium window of 46 mg cm^{-2}, the transmission at normal incidence is at least 0.8 down to 5 keV. The combination of the scintillator and window thus offers a very efficient detector over a wide energy range.	· The scintillator is very brittle and easily crazes with mechanical shock. · Window damage, which is not carefully repaired, will lead to a gradual deterioration of the scintillator, resulting in an increase in the energy threshold. · Quite expensive.
XENON FILLED, TITANIUM WINDOWED PROPORTIONAL COUNTERS	· Useful for β and low energy X and γ radiation. · Relatively tough window. · Light weight. · No gas filling required. · Consistent operating potential and radiation characteristics.	· Window not easily replaced. Repair/exchange costs can be expensive. · Higher background than all other types per unit area.

A1.6 Detector types suitable for different radiations

A1.6.1

Radiation type	Energy range	Detector type	Typical Characteristics
Low energy X, γ	From 10 keV	Ionisation chamber	Large volume detector required at protection level dose rates. Provides H*(10). Requires careful use. Expensive. Poor response at low dose rates. Flat energy response. Some instruments will have poor polar response at low energies.
		Thin end window GM tubes, energy compensated	Inexpensive. Energy response as good as ion chambers, good response at low dose rates.
		Plastic scintillator	Good energy response down to 20 keV. High sensitivity therefore useful at low dose rates.
		Thin sodium iodide detectors	Very high sensitivities at low energies. Very energy dependent. Difficult to use for dose rate assessment. Good for low energy photon sources and 'Search & locate'.
		Proportional counter	Uses gas amplification to produce a good signal at low dose rates.
Medium energy X, γ	From 60 keV	Compensated GM tube	Cheap and rugged. Operates well at low dose rates. Provides H*(10). Energy response not flat but generally within ± 30 % over range.
		Ionisation chamber	Large volume detector required at protection level dose rates. Provides H*(10). Requires careful use. Expensive. Poor response at low dose rates, flat energy response.
		Proportional counter	Uses gas amplification to produce a good signal at low dose rates. Expensive.
		Large volume sodium iodide detectors with a doserate capability	Very high sensitivity. Limited dose rate range (< 50 mSv h^{-1}). Expensive. Requires careful use.
β dose rate		Ionisation chamber	Large volume detector required at protection level dose rates. May provide H′(0.07). Requires careful use. Expensive. Poor response at low dose rates. Poor polar response.
		Thin end window GM tube	Sensitive, reasonable b energy response but poor X, g response.

A1.6.2

Radiation type	Energy range	Detector type	Comments
Alpha contamination	From 4 MeV	Solid state detectors	Good detection efficiency. Susceptible to RF and tend to be microphonic. Lightweight units. Expensive. Fragile detector.
		Zinc sulphide scintillator	Commonly available. Good sensitivity. Fragile foil. Can be g sensitive. Many different sizes.
		Thin end window GM	Fragile. Background countrate generally too high for most applications. No discrimination against other radiations. Small pancake GMs reasonably cheap.
		Large area gas re-fillable proportional counters	Tend to be expensive. Good detection efficiency. Require very high voltage. Discrimination against b radiation possible. Requires separate gas supply.
Beta contamination	From 0.15 MeV	Anthracene scintillator	Good sensitivity. Fragile foil. Many different sizes. During maintenance, handle with caution due to toxicity.
		Plastic scintillator	Readily available. Fragile foil. Many different sizes.
		Thin end window GM	Fragile. No discrimination against other radiations. Small pancake GMs reasonably cheap.
		Large area gas re-fillable proportional counters	Tend to be expensive. Good detection efficiency. Require very high voltage.
		Large area sealed proportional counters	Expensive. Good detection efficiency but not at low b energies due to rugged titanium window. Require very high voltage.
		Thin walled GM tubes	No good for bs with an E_{max}<0.5 MeV. Glass tubes can be very expensive.
Neutrons	From thermal energies	BF_3 proportional counter with spherical moderator	Poor sensitivity, typically 0.2 to 0.7 s^{-1} mSv^{-1} h for ^{241}Am-Be.
		^{3}He proportional counter with spherical moderator	Poor sensitivity, typically 0.2 to 0.7 s^{-1} mSv^{-1} h for ^{241}Am-Be.
		BF_3 proportional counter with cylindrical moderator	Poor sensitivity, typically 0.2 to 0.7 s^{-1} mSv^{-1} h for ^{241}Am-Be.
		LiI(Eu) scintillator with spherical moderator	Poor sensitivity, typically 0.2 s^{-1} mSv^{-1} h.
		Lightweight wide energy neutron scintillator	Good sensitivity. Limited gamma rejection. Lightweight

Appendix 2 Estimating surface activity

When monitoring takes place, operators are often given action levels which may be used to discriminate between acceptable and unacceptable conditions or, which if exceeded, may initiate additional actions. It is important therefore that these levels are based on factors which take into account the emissions from the radionuclide(s), the ability of a detector to measure them and the nature of the surfaces being monitored. To set these levels and estimate the surface activity present there are several related stages to consider:

- Identify the radionuclides likely to be present and their most significant emissions [11]. A simplified method of identifying the most significant emissions follows in Appendix A2.4.
- Determine the 2p efficiency from manufacturer's data or calibration data.
- Estimate what effect the surface conditions may have on the measurement, e.g. grime, paint, absorbency.

These factors are considered in turn below.

It should be emphasised that all calculations of surface activity make such a large number of assumptions that any results must carry a large uncertainty.

A2.1 Identification of significant emissions

The first step is to identify the emissions that can be detected with a relatively high probability above background, taking into account the operating conditions. For example, ^{241}Am on a clean, flat, non-absorbent surface can be detected easily using an α-probe (which has close to zero background). However, if there is a layer of grease on the surface the α particles will be absorbed and the significant emission will be the 60 keV γ ray, so a low-energy photon detector should be used.

Most radionuclides have complex decay schemes that make identifying the significant radiation more difficult. For example, ^{111}In has several decay paths - A2.4 shows a simplified version of the 18 separate pathways that lead to 406 different emissions. Some of these emissions occur in cascade, each will have a different detection efficiency and each will be absorbed to a different extent in the surface and in the detector window. Clearly, trying to work out the detection efficiencies of all of these emissions is an arduous task, so a simplified approach is necessary. Where multiple emissions are present, the main pathways should be considered in turn, identifying the most detectable emission in each pathway. As shown in A2.4, concentrating on the most detectable emission in each decay path means that the 2π efficiency will be underestimated, erring on the side of caution for radiation protection purposes.

Once the energies of the significant detectable emissions are known, the 2π efficiency for an 'ideal' source of that radiation type and energy can be determined by interpolation of the energy response curves, examples of which are shown in the next section.

A2.2 Estimating instrument response

Type test, manufacturer's data or calibration data can provide information on a particular instrument's energy response. This is usually established using high quality reference sources of a restricted range of radionuclides on ideal surfaces which do not mimic the types of surfaces that will be encountered in normal monitoring situations. Some typical energy response curves are shown in Figures 2, 3 and 4 for a, b and g radiation respectively.

Energy response curves can be used to estimate what a particular detector's 2p efficiency will be for 'ideal' sources of different radionuclides by identifying the energy and reading the corresponding detector efficiency from the curve.

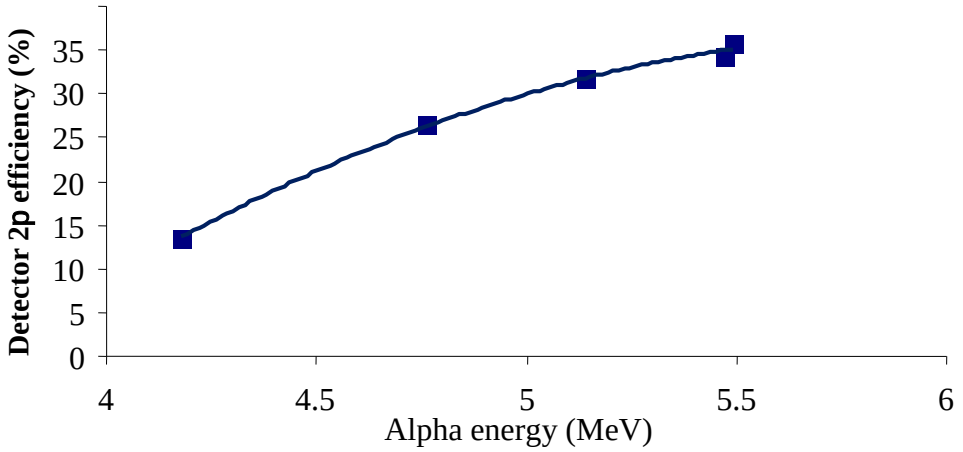


Figure 2: 2p efficiency vs alpha energy

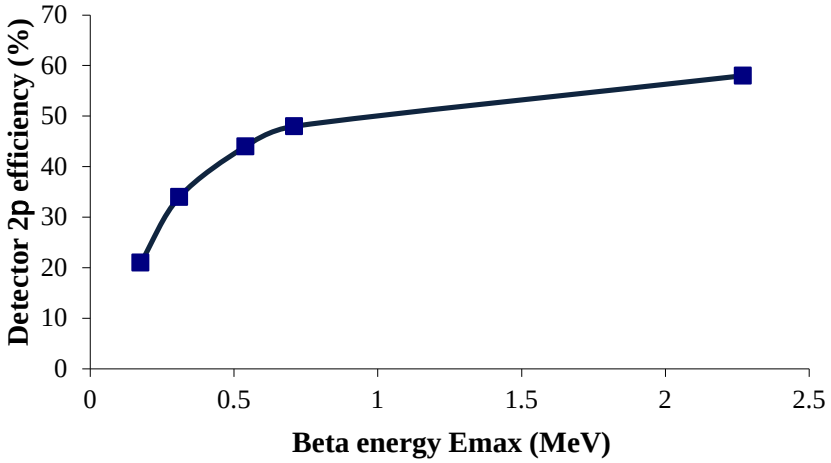


Figure 3: 2p efficiency vs beta energy

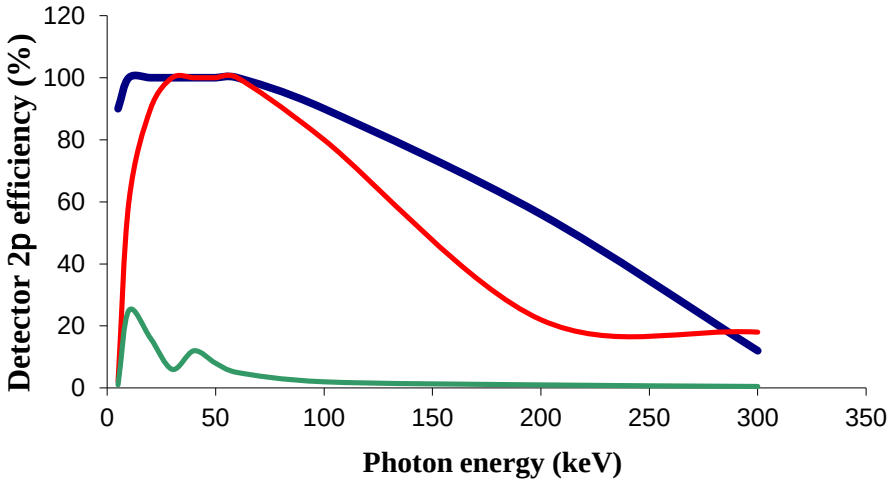


Figure 4: 2p efficiency vs photon energy

- NaI detector 3 mm thick, Be window 47 mg cm^{-2}

- NaI detector 2 mm thick, Al window 14 mg cm^{-2}

- Xe gas detector 20 mm thick, Ti window 5 mg cm^{-2}.

A2.3 Estimating surface effects

For some radionuclides, estimating surface activity from an observed number of counts can be a relatively simple process. For example, one Bq of ^{14}C will produce one beta particle per second (i.e. every single disintegration produces just one beta particle); this is referred to as an emission probability of 100 %. If the activity is distributed in a very thin layer, half of these particles will emerge from the surface and may impact on the detector window. If the appropriate 2p efficiency (which allows for any absorption of beta particles in the detector window) is applied to the observed counts, the resulting number displayed by the instrument is just half of the activity. To convert to the true activity, this number must be multiplied by a factor which is equal to 2. Historically, this has been referred to as the P factor.

The P factor was ‘adopted’ for a restricted range of single-emission radionuclides and was defined as the ratio of the number of particles generated by the source to the number emerging from the surface of the source in the direction of the detector. However, many radionuclides decay via several different decay paths and for each path, several emissions may occur in quick succession. Regardless of how many of these emissions from a single disintegration interact with the detector (one, several or all), only one event is registered by the instrument (this effect is known as ‘coincidence summing’, an example of this is shown in A2.4). It is clear that the simple P-factor definition above does not suffice for most radionuclides. In practice, using an instrument which would only respond to one type of emission may simplify the calculation of surface activity.

Only some of the emissions from a source or surface are detected. In order to estimate the activity, consideration must be given to what is present but not detected.

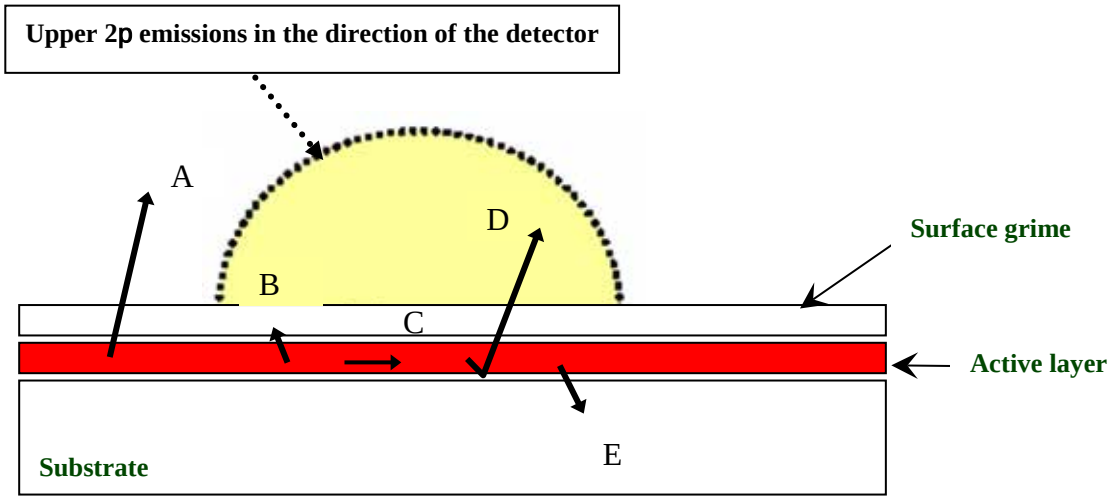


Figure 5: Schematic of emission processes from the surface of a source

The active layer of the source is shown in red

A: Particle/photon emitted from surface (may or may not interact in detector)

B: Particle/photon absorbed in surface grime (see Table 3)

C: Particle/photon absorbed in active layer (see Table 2)

D: Particle/photon back scattered from substrate (see Table 2)

E: Particle/photon absorbed in substrate.

Figure 5 shows what may happen to emissions that originate in the active layer of a source. Assumptions need to be made and an account needs to be taken of the number of emissions that could not possibly be registered by the detector or in the case of (D), emissions that add to the instrument response and potentially cause an increased estimate of activity.

Table 2 shows how some of these effects can be taken into account.

The surface effects illustrated can be categorized into 4 main components:

- Geometry

4p geometry describes the emissions that occur at all angles from the nucleus. 2p geometry describes those emissions from a source that are emitted in the direction of the detector. In the case of a perfect surface, half of the emissions go up and half of them go down.

- Backscatter

The effects of backscatter contribute to the observed reading, particularly if the contaminated surface is a high density material (for example some floors or stainless steel workbenches). However in practice, no correction is made for this because it only affects photons and high energy betas significantly and it results in an over estimate of the activity (see Table 2).

- Absorption in the active layer

When assessing alpha or low energy beta contamination, consideration must be given to particles that never leave the surface, i.e. self absorption. A reliable estimate of this effect can only be made if the active layer is small in relation to the range of emissions. See Table 2.

- Absorption in surface grime

When assessing alpha or low energy beta contamination, consideration must be given to any coatings (e.g. paint or varnish) or any material that may be deposited on the contaminated surface (e.g. polish or dust) as these will absorb a proportion of the emissions. See Table 3.

By applying a correction for these surface effects to the surface activity calculated for 'ideal' contamination of this radionuclide, it is possible to estimate a more realistic value for the activity of the real contamination. However, if the 'ideal surface' 2p detector efficiency is used, any action levels set will be too high.

Effect	**Radiation affected**	**Magnitude of effect on the number of counts registered** **and** **how it can be accounted for**
Ideal surface	All	Multiply number of counts by 2 to account for emissions occurring in the opposite direction to the detector

Non ideal surfaces		**In addition to the factor of 2 above**
Backscatter	High energy b and γ	Increases surface emission by 10-20 % on high atomic number backings (e.g. steel). **Reduce counts by 10-20 % before multiplying by the factor of 2 for an ideal surface**
Self absorption in the active layer	Alphas	Relatively thin deposits can result in a considerable reduction in surface emission rates. **Multiply counts by an additional factor of at least 2 for all alphas except very thin deposits.**
	Low energy bs (0.15-0.4 MeV)	Relatively thin deposits can result in a considerable reduction in surface emission rates. **Multiply counts by an additional factor of at least 2 for all low energy betas except very thin deposits.**
	High energy bs	Surface emission unaffected for thin deposits (ie, deposits less than 1 mg cm^{-2} thick).
Surface coatings More details provided in Table 3	Alphas	A grime layer 5 mg cm^{-2} (a sheet of paper) thick totally absorbs a radiation. **Multiply by a factor of at least 2. The figure to be used rapidly approaches infinity (total absorption).**
	Low energy bs	A grime layer 5 mg cm^{-2} thick decreases surface emission by a factor of 2 or more. **Multiply counts by an additional factor of at least 2 for all low energy betas.**
	High energy bs	A grime layer 5 mg cm^{-2} thick does not significantly change surface emissions.

Table 2: Typical correction factors for absorption of radiation[6]

		Radionuclide and radiation type				
		^{238}Pu	^{14}C	^{36}Cl	^{90}Sr + ^{90}Y	^{55}Fe
		Alpha	Soft beta	Medium beta	Medium + hard beta	5.9 keV photon
Coating	**Mass per unit area (mg cm^{-2})**	**Percentage Transmission Values**				
Car paint	2.6	10	50	90	95	30
Anti-rust paint	4.0	0	30	90	95	35
Lacquer	2.4	10	50	90	95	50
Wood varnish	1.4	30	60	95	100	70
Furniture polish	0.1	90	95	100	100	95
Oil as applied	1.3	30	70	95	100	70
Oil wiped off	0.14	90	95	100	100	95
Grease as applied	1.8	20	60	95	100	60

The paints are one coat only. The polish is two coats. All are applied according to manufacturers' instructions.

Table 3: Percentage transmission factors for surface coatings[6]

Example calculation – estimating surface effects

Even measuring a commonly-used radionuclide such as ^{14}C can be problematic. Suppose a laboratory coat has been contaminated with ^{14}C. Factors to take into account in estimating the activity using a surface contamination monitor include:

Factor	Data source	For this example
Source characteristics	From Decay Data Evaluation Project (DDEP) database	Pure beta emitter, maximum (end-point) energy: 0.15 MeV
Area of probe	From manufacturer's data sheet	A = 10 cm^2
Detector 2π efficiency	From manufacturer's data or calibration certificate	2πeff = 0.20 (i.e. 20 %)
4π geometry	Table 2	Factor of 2
Observed count rate	Measured	R = 20 counts per second
Background count rate	Measured	B = 5 counts per second
Distance from probe to surface of laboratory coat	Estimated	3 mm
Backscatter	Table 2	Negligible at 0.15 MeV
Self absorption in active layer	Table 2 & 3	Consideration required as layer is more than a very thin deposit
Surface coatings/absorbent surface	Table 2 & 3	No surface coating in this case but the surface is very absorbent

Neglecting self absorption for the moment and assuming that the monitor was calibrated at a distance of 3 mm from the reference source, the surface emission rate from the laboratory coat can be calculated from the equation in section 7.2.2:

$$SER = 100 \times \frac{R - B}{A \times 2\pi\text{eff}}$$

The surface emission rate from the laboratory coat was therefore 7.5 betas cm^{-2} s^{-1}. The activity on the surface was 15 Bq cm^{-2} as ^{14}C emits one beta particle per decay but 50 % do not reach the probe (a P-factor of 2).

The effects of self absorption/surface absorption in the material of the coat now need to be considered. It is impossible to estimate the self absorption as it is completely soaked into the laboratory coat, however the effects of the material can be estimated. Table 3 shows that a layer of material only 4 mg cm^{-2} thick will transmit 30 % of the betas emitted in the decay of ^{14}C. Assuming, for the purposes of this example, that the activity is at an average effective depth in the material of 4 mg cm^{-2}, the actual activity would be at least three times the original estimate.

This simple example highlights the difficulty in estimating activity (Bq) on surfaces using surface contamination instruments. Other methods such as laboratory analysis of samples or experimental studies may be needed, depending on the application.

A2.4 Example of decay scheme correction: ^{111}In

Most radionuclides have complex decay schemes. As an example, a simplified decay scheme of ^{111}In is shown in Figure 6.

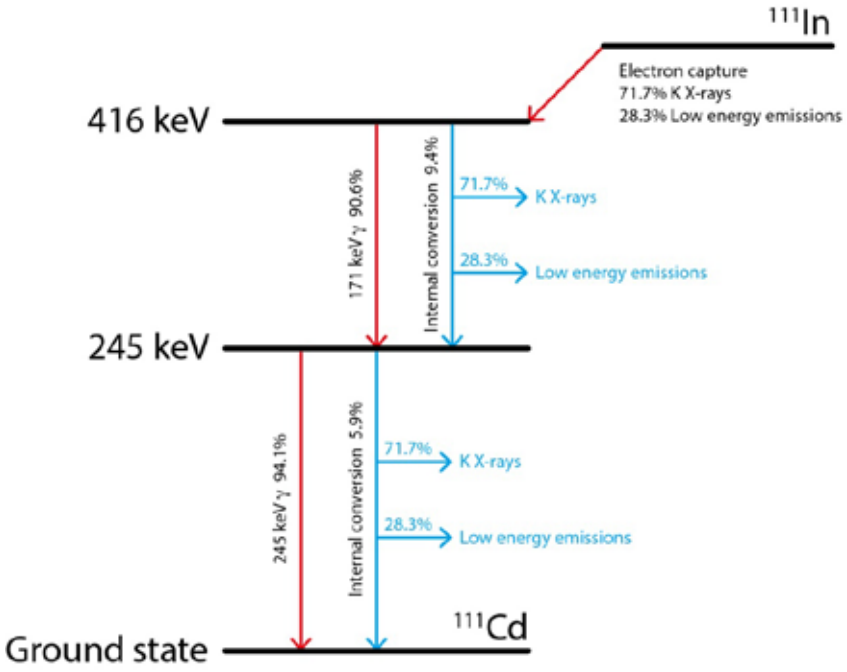


Figure 6: ^{111}In decay scheme

^{111}In decays through three separate stages:

Stage 1: transition from the ground state of ^{111}In to the 416 keV excited state of ^{111}Cd

This electron capture process results in K X-rays being emitted in 71.7 % of the times and, in the other 28.3 % of times, particles or photons which will not be detected in the photon probe are emitted

Stage 2: transition from the 416 keV excited state of ^{111}Cd to the 245 keV excited state

90.6 % of these transitions emit a 171 keV gamma. In the other 9.4 % of transitions, a conversion electron is produced and that is followed either by K X-rays (in 71.7 % of times) or by particles or photons which will not be detected (in 28.3 % of times)

Stage 3: transition from the 245 keV excited state of ^{111}Cd to the ground state

94.1 % of these transitions emit a 245 keV gamma. In the other 5.9 % of transitions, a conversion electron is produced and that is followed either by K X-rays (in 71.7 % of times) or by particles or photons which will not be detected (in 28.3 % of times)

Thus the total number of 171 keV gammas that are emitted per decay is 91 % and the total number of 245 keV gammas that are emitted per decay is 94 %. For the K X-rays, there are 71.7 % per decay arising from stage one, 6.7 % per decay from stage 2 (i.e. 71.7 % of 9.4 %) and 4.2 % per decay from stage 3 (i.e. 71.7 % of 5.9 %), giving a total of 83 %.

All of the emissions, including those which will not be detected by the probe, are summarised in the table below. The type of probe used in this example is a NaI detector, 2 mm thick, Al window 14 mg cm^{-2}. The 2π efficiencies in table 4 below are estimated approximately from the graph in Figure 4 (red line). The particle emissions (Auger and conversion electrons) are not detected because the probe window absorbs them.

Emission	**Energy (keV)**	**Emissions per decay (%)**	**2π Efficiency from Figure 4**	**Comment**
L Auger electrons	3 - 4	100	0	Absorbed by probe window
K Auger electrons	19 - 26	16	0	Absorbed by probe window
Conversion electrons	140 - 250	15	0	Absorbed by probe window
K X-rays	23 - 27	83	0.9	Emissions of similar energies can be grouped for the purpose of this approximation
Gamma	171	91	0.4	In most cases, the 171 and 245 keV gammas are emitted simultaneously
Gamma	245	94	0.15	

Table 4: Summary of ^{111}In emissions and 2π detection efficiencies

An estimate of the instrument response can be calculated as follows. The most abundant branch is indicated by the red coloured arrows in the decay scheme above. The following emissions occur:

Stage 1: K electron capture resulting in: K X-ray (~ 72 % of decays)

Stage 2: gamma transition resulting in: 171 keV photon (~ 91 % of decays)

Stage 3: gamma transition resulting in: 245 keV photon (~ 94 % of decays)

First, assume the monitor only detects the K X-rays (stage 1). If there is a point source of 1000 Bq under the monitor, the observed net count rate will be approximately:

= activity x emission probability x detection efficiency (4π)

= 1000 x 0.72 x 0.90 x 0.5

= 324 counts per second

(The factor of 0.5 is needed as the detection probability stated in table 4 is for emission into 2π. The factor of 0.72 is the emission probability, rounded for simplicity.)

If the monitor also detects the gamma transitions, the observed count rate will be higher. The problem is that the emissions are simultaneous, so detecting a gamma transitions only adds to the observed count rate if the preceding X-ray has been missed. The easiest approach to solving this problem mathematically is to determine the probability of **not** detecting any of the emissions. This is calculated as follows:

Probability of missing stage 1 = (1.0 – 0.72 x 0.90 x 0.5) = 0.676

Probability of missing stage 2 = (1.0 – 0.91 x 0.40 x 0.5) = 0.818

Probability of missing stage 3 = (1.0 – 0.94 x 0.15 x 0.5) = 0.930

The probability of missing all three emissions is given by the probability of missing stage 1 **and** missing stage 2 **and** missing stage 3; from probability theory, this is simply the product of the three probabilities = 0.676 x 0.818 x 0.930 = 0.514.

The observed net count rate is therefore = 1000 x (1.0-0.514) = 486 counts per second.

The observed count rate (instrument response) is therefore higher if we take into account more emissions in the decay scheme. The estimated count rate increases further if we include (in a similar way) the probability of detecting other transition paths, but these calculations become complex.

The calculations are also more complex if there is a significant absorbant layer over the contamination (or if the contamination is absorbed into the surface). For example, a layer of grease on the surface will transmit, for example, 30 % of the X-rays but the higher energy gammas will be unaffected. The probability of missing stage 1 will increase to:

Probability of missing stage 1 = (1.0 – 0.3 x 0.72 x 0.90 x 0.5) = 0.9028

The effect of the grease will be to change the observed count rate to 313 counts per second.

It is therefore feasible to develop a mathematical model of the instrument response so that the activity on the surface can be estimated from instrument readings for radionuclides with complex decay schemes. Provided there is a relatively dominant decay path, the surface effect factors are applied separately to individual emissions and the coincident summing is taken into account, the approximation method can be employed in many situations.

However, as these calculations show, there are many competing effects and use of other techniques (high resolution gamma spectrometry and laboratory analysis) should be considered.

Appendix 3 Interpretation of manufacturer's type test data – photon dose rate

Often in the workplace, the mean photon energy is likely to be unknown and some assumptions need to be made.

For example, in order to take a measurement of tube leakage from an X-ray set operating at 80 kVp, an assumption is made that the mean energy penetrating the X-ray tube shielding is close to 80 keV.

A compensated GM tube would be suitable for the measurement of leakage due to its high sensitivity. The manufacturer should provide data on how an instrument performs at different energies; a typical energy response curve for this type of detector is shown below. The points where a calibration is normally carried out are circled (60 keV and 662 keV) and the response of the detector at other energies is plotted against the relative response to 662 keV.

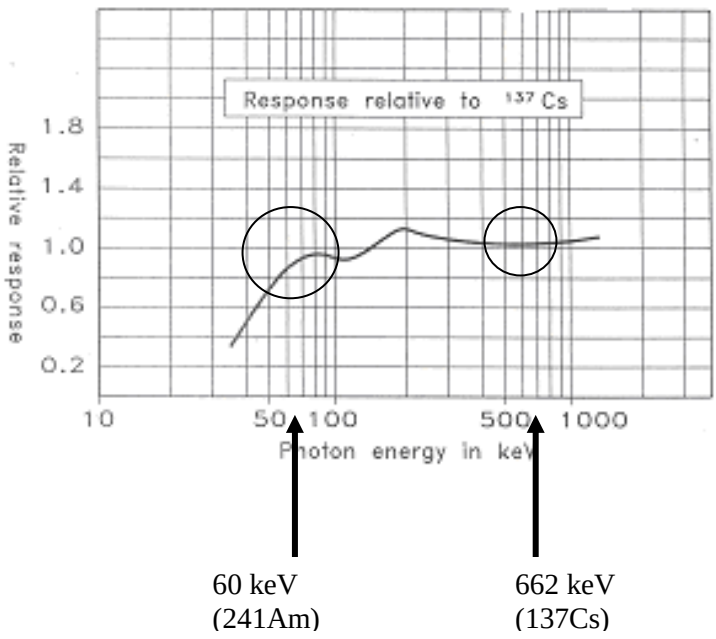


Figure 7: Typical response curve for a compensated GM detector showing calibration points

Below 80 keV, the rate of change of response is quite dramatic. From the curve above it can be seen that the response at 80 keV is approximately 0.95, or 95 %, of the response at 662 keV.

In practice, many users choose to assume that the indication on the instrument is absolutely correct because the calibration confirmed that the instrument was performing to within ± 30 % of its expected response. This may be perfectly acceptable in some circumstances however to reduce the uncertainty of a measurement, the instrument's relative response to a calibration source may applied (see below). Further information on sources of uncertainties is provided in Section 7.4.

Using data provided on a calibration certificate for the actual response of the instrument at 662 keV, the correction for the response at 80 keV can be determined.

If the calibration certificate quotes an instrument response, I_R of 1.1 for ^{137}Cs, and the instrument's relative response at 80 keV is 0.95, the estimated response at 80 keV would be:

$$1.1 \times 0.95 = 1.04$$

The net instrument reading should be divided by 1.04 to give the best estimate of the dose rate at 80 keV.

Appendix 4 Speed of measurement with a contamination monitor

Monitoring speed, that is the speed at which a probe can be moved over a surface to ensure a reliable assessment of contamination levels, needs to be carefully assessed prior to any survey. Many factors affect monitoring speed but in perfect conditions monitoring speeds can be much faster than intuition would suggest; the reasons for this are given below. For efficient monitoring, use can be made of the averaging area allowed for routine measurements. However, direct monitoring in practice is more cautious as the averaging area of the probe is commonly used. Monitoring speeds are therefore typically much slower.

A4.1 Monitoring for beta contamination

A typical Derived Limit (DL) or maximum acceptable level for b contamination is 4 Bq cm^{-2}. A typical probe will have an active area of 100 cm^2 and a response of 10 to 20 s^{-1} Bq^{-1} cm^2 to b radiation (dependent on energy). Hence the probe response to a DL will be 40 to 80 s^{-1}.

Assume a ratemeter is a recycling scaler, i.e. one that counts for a fixed period, displays the answer in counts per second and then restarts, and displays the answer at the end of each counting period. If the counting time is n seconds, the probe width is x cm and the permitted averaging area is A cm^2 then the maximum monitoring speed is given by A/nx.

If typical values of n =2 s, x =7 cm and A=1000 cm^2 are taken, then the maximum monitoring speed is 70 cm s^{-1}, which is very fast indeed.

If a large area of 1000 cm^2 were to be monitored and the maximum acceptable level for β contamination spread evenly over it was 4 Bq cm^{-2}, the activity that must be present to exceed this limit would be (4 x 1000) = 4000 Bq, or 4 kBq. The probe, having a response of 10 – 20 s^{-1} Bq^{-1} cm^2 would undoubtedly produce a clear response. On the other hand, 4 kBq could be localised in a small area. Although the probe passes rapidly over this area, the concentration of activity is such that the probe will still respond.

A4.2 Monitoring for alpha contamination

A typical DL for a contamination is 0.4 Bq cm^{-2}. A typical probe will have an active area of 100 cm^2 and a response of 16 s^{-1} Bq^{-1} cm^2. Hence the probe's response to a derived limit of alphas will be about 6 s^{-1} (0.4 ´ 16). This is significantly more than the normal background rate (<1s^{-1}).

A good surveyor will pause on each beep when working at low levels. If the expected countrate at the maximum acceptable level is 6 s^{-1} then the chance of 'no beeps' is very small. Therefore the whole 1000 cm^2 can be swept in one second and the speed would be 100 cm s^{-1} based on a 10 cm probe width. The probe would either pass over 400 Bq uniformly distributed across 1000 cm^2, or pass over a small area in which 400 Bq of a contamination was concentrated (i.e. the equivalent of a small a source). Either way it is almost certain the probe will register the presence of a contamination.

However, if the DL is reduced to 0.04 Bq cm^{-2} then the maximum acceptable average count rate drops to 0.6 s^{-1}. To guarantee at least one count in each period, a 10 second count is required on the area of interest to give a mean of 6 counts. If the averaging area is only 300 cm^2 (e.g. the averaging area when monitoring the human body) the sweep speed drops to virtually nothing, 300/10x10, or 3 cm s^{-1}. In practice this will require the surveyor to do a stationary reading for 10 seconds and then move one probe dimension for the next reading and so on, in order to ensure that a contamination levels are less than 0.04 Bq cm^{-2}.

In conclusion, monitoring speeds are very dependent on the derived limits. If the derived limit is set so that the probe response to the derived limit is equivalent to the probe/ratemeter background count then monitoring to clearance levels will be painfully slow. If, however, the derived limits are set so a good response can be expected from the probe then clearance monitoring can be surprisingly quick.

Appendix 5 Common failure modes for monitors

A5.1 General problems

General problems can arise because of poor battery contact, leading to erratic operation. It is important that only one type of battery is used, as battery lengths vary considerably between types and manufacturers brands. Fitting a short-lived battery after a long-lived one may lead to poor contact. Flat spring connectors are more prone to failure than coil spring designs. Battery contact corrosion is also a problem in old or badly maintained units, especially where batteries have leaked.

Cables and connectors may also cause problems. The PET connector, which is standard on UK instruments, and the MHV connector are not strong enough to support the weight of a probe on a regular basis. Damage to connectors can lead to intermittent contact or high background count rates. Cables can also be damaged by pulling them too tight, cutting them on sharp corners or closing them in instrument carrying-case lids.

Conventional meters can also be damaged by impact. The glass can smash or the free movement of the needle can be restricted. Impact can damage instrument cases and circuit boards and can also generate cracks in glass to metal seals in Geiger Muller detectors.

The internal structure of photomultiplier tubes is also vulnerable to damage, as is the optical coupling with the scintillator. It is important to use the correct optical coupling liquid as otherwise this can lead to many problems not least incorrect sensitivity.

Contamination of monitors can lead to contamination of the user and the spread of contamination generally. The normal indication that an instrument is contaminated is a high background count rate. This is a particular problem when monitoring for a contamination, where a very low background is normally essential.

A5.2 Specific problems

Ion chambers

The air inside an ion chamber must be kept dry. If the desiccant becomes exhausted then the background tends to increase, either positive or negative, and the level of fluctuation increases. The desiccant should be dried according to the manufacturer’s instructions. The instrument should also be dried by placing it in a warm (+40 °C) dry place for several hours. Storage of ion chambers in elevated radon concentrations may cause the instrument background to fluctuate significantly because of the decay of radon that has diffused into the chamber. Removal to a low radon area and ventilation of the instrument will remove the problem in a few hours.

End window Geiger Muller detectors

These are very vulnerable to damage by contact with anything that is at all rigid, such as tools, swarf and grass stems. The detectors can implode and replacement of the whole detector is the only option. The conductive coating (DAG) may flake or inadvertently get removed by solvents, this will affect the performance of the detector.

Thin window alpha and beta scintillation detectors

Damage to these generally results in a light leak, leading to high background count rates or whistling noises. The foil can be replaced relatively easily. Photomultiplier tubes are susceptible to magnetic interference.

Sealed thin window proportional counters

These do not implode, but gradually lose their sensitivity if punctured. Total replacement is the only option but this is expensive.

Sodium iodide scintillation detectors

Window damage leads to light leakage or the formation of yellow patches where water has entered (which effectively increases the energy threshold and reduces the sensitivity). Impact can result in shattering of the crystal, leading to a very marked loss of sensitivity. Photomultiplier tubes are susceptible to magnetic interference.

Appendix 6 Estimation of surface contamination by mixed radionuclides

If more than one radionuclide is involved, and the relative activities are unknown, then the estimation of activity for the individual components will be a complex issue. First the radionuclides involved must be identified; often the history of the facility will be sufficient to determine these. In other circumstances, it may be necessary to use gamma spectrometry or radiochemical separation and analysis to identify the radionuclides present. Alternatively, there may be some situations where some simple processes may be applied using a portable contamination monitor, which can provide estimates with uncertainties which are acceptable for the particular investigation. Clearly, each situation needs to be assessed separately.

The two examples below describe scenarios whereby some relatively simple measurements can be made which allow the determination of the activity of the individual radionuclides.

Example 1 – ^{14}C and ^{99m}Tc mix

The example uses a dual purpose probe which is commercially available from a mainstream manufacturer to estimate the activity of contamination from a mixture of ^{14}C and ^{99m}Tc. The probe combines a thin aluminized melinex window with a thin sheet of CsI scintillator. It is intended mainly for life sciences use, where both low energy betas, such as ^{14}C, and low energy X or gamma emitters, such as ^{99m}Tc, are in use. Note that this probe is very different to conventional beta scintillation probes, which are often incorrectly referred to as 'beta/gamma' probes; the latter have a very low gamma detection efficiency.

The probe is supplied with a cover (absorber) that has a thickness of 1 mm plastic. A measurement is first made with no cover present and the reading noted, this measures the emissions from both radionuclides. The measurement is then repeated with the cover in place and the reading noted again. The cover absorbs all of the beta particles from ^{14}C. For the ^{99m}Tc, a fraction of the 18-21 keV X-rays will be absorbed and also, to a much lesser extent, the 140 keV gammas.

For this example, it is assumed that the overall effect of the absorber is to reduce the ^{99m}Tc emissions reaching the detector probe by an amount which equates to a 15 % reduction in the reading. This reduction could either be estimated theoretically or experimentally, if facilities are available. Hence we have:

Count rate observed from open window (no cover) 2000 s^{-1}

Count rate observed with cover (i.e. due to ^{99m}Tc alone) 1200 s^{-1}

From manufacturer's data for this detector:

$I_R(A)$ for ^{14}C (no cover) = 3.5 cps per Bq cm^{-2}

$I_R(A)$ for ^{99m}Tc (no cover) = 12 cps per Bq cm^{-2}

From the assumptions made above, the following figures can be adopted for the cover in place

$I_R(A)$ for ^{14}C (with cover) = 0.0 cps per Bq cm^{-2}

$I_R(A)$ for ^{99m}Tc (with cover) = 0.85 x 12 cps per Bq cm^{-2} = 10.2 cps per Bq cm^{-2}

The surface activity for ^{99m}Tc is calculated from the reading with the cover in place:

1200 / 10.2 = 118 Bq cm^{-2}

Hence, the ^{99m}Tc contribution to the instrument reading with no cover in place, would be:

= 118 x 12 = 1416 cps

And therefore the ^{14}C contribution to the reading with no cover in place would be:

2000 – 1416 = 584 cps

And the activity of ^{14}C = 584/3.5 = 167 Bq cm^{-2}

Greasy surface effect on instrument response

Assume a thin layer of grease covers the surface being measured and that the grease will absorb 40 % of the ^{14}C beta emissions (see Table 3). It can also be assumed that the grease absorbs 5 % of the ^{99m}Tc emissions. The instrument readings will be affected and we now observe:

Count rate observed from open window (no cover, grease) 1698 s^{-1}

Count rate observed with cover (i.e. due to ^{99m}Tc alone, grease) 1140 s^{-1}

The instrument response factors, corrected for the effects of the grease are:

$I_R(A)$ for ^{14}C (no cover, grease) = 0.6 x 3.5 cps per Bq cm^{-2} = 2.1 cps per Bq cm^{-2}

$I_R(A)$ for ^{99m}Tc (no cover, grease) = 0.95 x 12 cps per Bq cm^{-2} = 11.4 cps per Bq cm^{-2}

$I_R(A)$ for ^{14}C (cover, grease) = 0.0 cps per Bq cm^{-2}

$I_R(A)$ for ^{99m}Tc (cover, grease) = 0.85 x 11.4 cps per Bq cm^{-2} = 9.7 cps per Bq cm^{-2}

Using these values gives a ^{99m}Tc activity from the covered reading of:

1140/9.7 Bq cm^{-2} = 118 Bq cm^{-2}

The instrument reading with no cover in place due to ^{99m}Tc alone would then be 118 x 11.4 cps = 1345 cps.

This gives a ^{14}C contribution to the no cover reading of 1698 – 1345 cps = 353 cps.

This then leads to a ^{14}C activity of 353/2.1 Bq cm^{-2} = 168 Bq cm^{-2}

Example 2: mixed beta emitters

The process for estimating the surface activity of a mix of beta emitters involves a series of steps:

- Identify the radionuclides of interest.
- For each radionuclide, tabulate the decay scheme, in terms of probability of following a particular decay path and the corresponding maximum beta energy.
- Take the type test data for each radionuclide and tabulate the response against the maximum beta energy. If the radionuclide in question is a gamma emitter with a relatively low energy beta emission, the response will also include counts generated by the gamma emissions.
- Produce a graph of response against maximum energy (note that care should be taken in interpreting the type test data for ^{90}Sr + ^{90}Y – it may be necessary to correct the high energy ^{90}Y response for the low energy ^{90}Sr response). Note that the dual energies from ^{90}Sr + ^{90}Y can cause a problem.
- The graph can then be used to estimate the response to a 100 % emission at each of the beta energies of interest. These values should be tabulated appropriately.
- For each radionuclide to be monitored, the predicted response can be obtained by summing the product of emission probability and predicted response over all the energies present.
- Taking this further, the response to a mixture can then be determined by multiplying the fraction of each radionuclide by the corresponding predicted response.

As an example, consider an instrument with a 100 cm^2 thin windowed scintillation detector with a useful response from ^{14}C upwards.

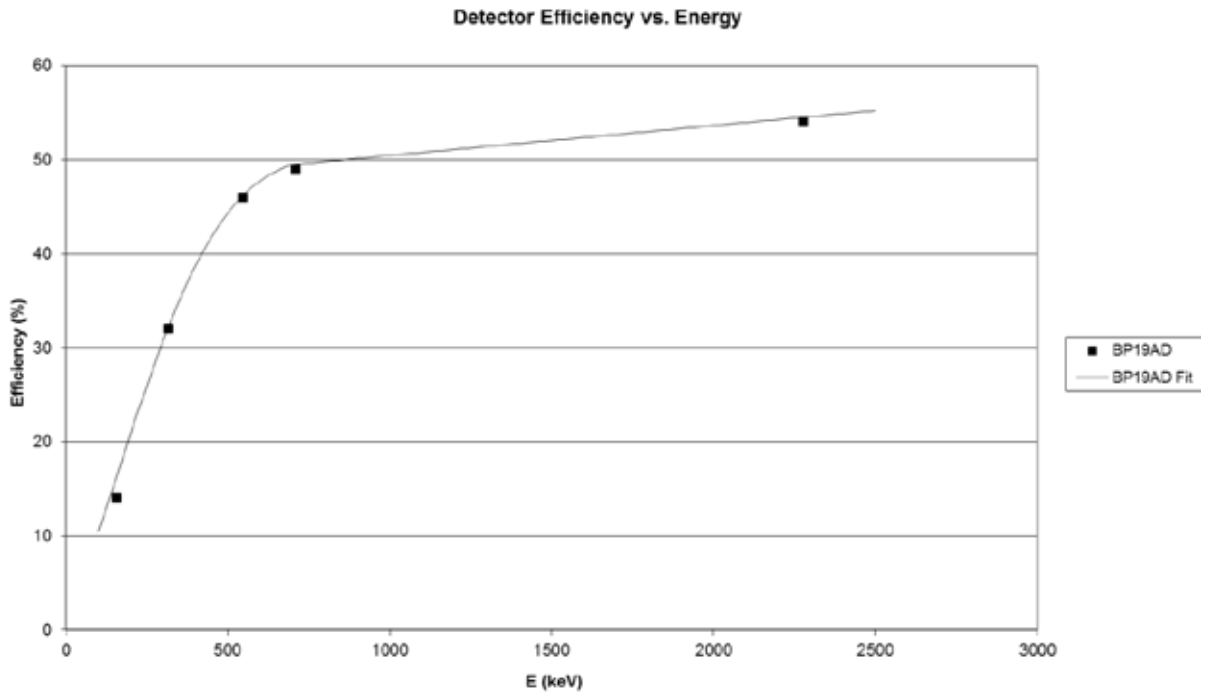


Figure 8: Detector efficiency vs energy

Data from ^{14}C, ^{60}Co, ^{90}Sr, ^{36}Cl and ^{90}Y are plotted (^{60}Co data were checked to ensure that the response to the gammas emitted in the decay of this radionuclide were excluded from the type test data). Extrapolating at the low energy end will produce an intercept with the X axis. This represents the minimum energy for which a full energy beta particle emitted normal to the surface will just penetrate the window. The response rises quickly after that as more of the beta particles have enough energy and are emitted sufficiently normal to the surface to be detected. Ultimately, for ^{90}Y, almost all particles which do not collide with the protective grille will be detected. Most beta detectors will produce a similar graph, mainly varying in the minimum detectable energy.

The detection probabilities for the beta emission in the radionuclides may be estimated using the above graph. ^{125}Sb, for example, is shown in the table below:

Beta energy (keV)	**Emission probability**	**Predicted 2 π efficiency (%)**	**Emission probability x predicted 2 π efficiency**
95	0.135	0	0
125	0.058	0	0
131	0.181	0	0
241	0.016	23	0.4
303	0.403	31	12.5
446	0.071	42	3.0
622	0.136	48	6.5

Table 5: Emission probabilities for ^{125}Sb

The total efficiency (sum of the emission probabilities x predicted 2 π efficiencies) is thus 22.4 %, which rounds to 22 %. Taking the probe area as 100 cm^2 gives a predicted response of 11 cps Bq^{-1} cm^2.

Consider, now, a fingerprint which is composed of 30 % ^{137}Cs, 25 % ^{125}Sb, 12 % ^{14}C and 33 % ^{3}H. The response to the fingerprint is illustrated below.

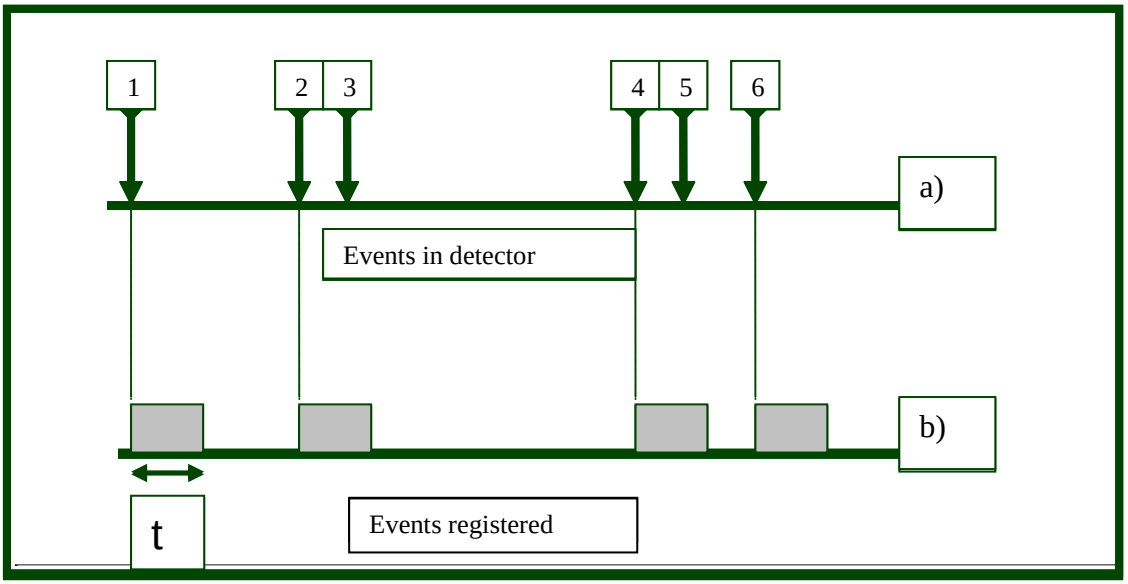
Radionuclide	**Measured or predicted 2 π efficiency (%)**	**Fingerprint fraction**	**Contribution (%)**
^{137}Cs	42	0.30	12.6
^{125}Sb	22	0.25	5.5
^{14}C	16	0.12	1.9
^{3}H	0	0.33	0

Table 6: Response to mixed radionuclide

The total is then 20 % 2 π efficiency, giving an estimated response as 10 cps/Bq/cm^2 for the detector. This figure can then be used to estimate the approximate activity on the surface, although care must be taken with interpreting the results.

Appendix 7 Correction for dead time

Pulse counting instruments such as GM detectors and the majority of proportional and scintillation counters may underestimate the number of pulses at very high counting rates. This is because there is a time needed to process the interaction and during that time, no further pulses will be registered; this is known as the dead time or paralysis time. Dead times range from a few µs for scintillation and the smallest GM types to a few hundred µs for larger GM types. The effect of dead time is shown in the figure below:



where t =deadtime of detector following an interaction

Figure 9: Effect of dead time on registered count rate

Event number	1	2	3	4	5	6
Counted?	ü	ü	X	ü	X	ü

A total of 6 events occur within the detector (a) but only 4 counts are registered (b).

Events 3 & 5 will not be registered because they occur during the dead time period of the detector.

If dead time correction is not automatically made by the instrument (consult the instrument manual to confirm), a correction will have to be applied to any results at high counts.

The observed count rate can be corrected for dead time using the formula below:

$$\text{True count rate} = \frac{R_i}{1 - R_i\tau}$$

Where R_i is the instrument indication and τ is the dead time for the detector in seconds.

If a GM tube has a dead time of 25 μs and R_i is 2000 s^{-1},

$$\text{the true count rate} = \frac{2000}{1 - 2000 \times 2.5 \times 10^{-5}}$$

$$= 2105\ s^{-1}$$

In this example, there is a loss of 5 % of the counts (2000/2105) due to the dead time.

References & other useful sources of data

1 The Ionising Radiation Regulations 1999, HMSO, 1999.

2 Radioactive Substances Act 1993, HMSO, 1993 and Environmental Permitting Regulations, 2010.

3 National Physical Laboratory, Measurement Good Practice Guide No.14, *The Examination, Testing & Calibration of Portable Radiation Protection Instruments*, NPL.

4 National Physical Laboratory, Measurement Good Practice Guide No.29, *The Examination, Testing & Calibration of Installed Radiation Protection Instruments*, NPL, 2001.

5 International Organisation for Standardisation, *Reference Sources for the Calibration of Contamination Monitors*, BS ISO 8769, 2010.

6 P H Burgess, *Handbook on measurement methods and strategies at very low levels and activities*, European Commission Report EUR 17624, 1998.

7 AEA Technology plc, *The Radiochemical Manual 2nd edition*, AEA Technology plc, 1998.

8 International Commission on Radiation Protection, *Radionuclide transformations*, ICRP Report 38, 1983.

9 Richard B. Firestone, Virginia S. Shirley, *Table of Isotopes*, 1996.

10 International Organisation for Standardisation, *Evaluation of Surface Contamination*, BS ISO 7503 parts 1 – 3, 1988.

11 P H Burgess, *Guidance on the Choice, Use and Maintenance of Hand-Held Radiation Monitoring Equipment*, NRPB R326, 2001.

12 International Commission on Radiation Protection, *Conversion coefficients for use in Radiological Protection against External Radiation*, ICRP Report 74, 1997.

13 www.nucleide.org/DDEP_WG/DDEPdata.htm

14 www.radprocalculator.com/RadDecay.aspx

15 H. Jung et al, *Consistency and Efficiency of Radiological Standard Swipe Procedures Taken on Slightly Radioactive Contaminated Metal Surfaces*, Health Physics, 80, Supplement 2, 2001.

16 *Conversion Coefficients for Use in Radiological Protection against External Radiation*. ICRU Report 57 (ICRU Publications: Bethesda), 1998.

17 *Radiation Shielding for Diagnostic X-rays*, BIR/IPEM Report, British Inst of Radiology, 2000, IBSN 0-905749-44-8.

18 Environment Agencies Requirements Working Group (http://www.rwbestpractice.co.uk/)

19 National Physical Laboratory, Measurement Good Practice Guide No.34, *Radiometric Non-Destructive Assay*, NPL, 2003.

20 National Physical Laboratory, Measurement Good Practice Guide No.82, *The Examination and Testing of Equipment for Monitoring Airborne Radioactive Particulate in the Workplace*, NPL, 2006.

21 National Physical Laboratory, Measurement Good Practice Guide No.113, *The Examination and Testing of Electronic Personal Dosemeters*, NPL, 2011.

22 National Physical Laboratory, Draft Measurement Good Practice Guide No.114, *The Examination and Testing of Tritium Monitors*, NPL.

23 National Physical Laboratory, Measurement Good Practice Guide No.49, *The Assessment of Uncertainty in Radiological Calibration and Testing*, NPL, 2003.

24 GUM, BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, *Guide to the Expression of Uncertainty in Measurement*, ISO, Geneva, Switzerland. ISBN 92-67-10188-9, First Edition 1993, corrected and reprinted 1995.

25 M3003, UKAS Publication M3003, *The Expression of Uncertainty and Confidence in Measurement*, Edition 3, November 2012.

26 National Physical Laboratory, Measurement Good Practice Guide No. 11, *A Beginner's Guide to Uncertainty of Measurement*, NPL Measurement Good Practice Guide No. 11, 1999.

27 Tanner et al, *Practical Implications of Neutron Survey Instrument Performance*, HPA Report HPA-RPD-016, November 2006.

Glossary

Ambient (as applied to dose rate, etc)	the normal background condition in the absence of any artificial source of ionising radiation.
Ambient dose equivalent H*(10)	the dose equivalent that, at a point in a radiation field, would be produced by the corresponding expanded or aligned field, in the ICRU sphere, at a depth of 10mm on the radius opposing the direction of the aligned field. The unit is Sievert, Sv
Directional dose equivalent H'(0.07)	the dose equivalent that, at a point in a radiation field, would be produced by the corresponding expanded field in the ICRU sphere at a depth of 0.07mm on a radius in a specified direction. The unit is Sievert, Sv.
Backscatter	the deflection of radiation or nuclear particles by scattering processes through angles greater than 90° with respect to the original direction of travel.
Becquerel	one nuclear disintegration per second.
Collimated beam of radiation	a beam of radiation, whose rays or particles are constrained so that the beam diverges slowly.
Crystallography	determination of crystal structures using low energy X-rays.
Deposition depth	the maximum depth below the surface to which the radioactive material is incorporated.
Derived limit	a lower limit of contamination that is considered acceptable and practicable to remain without further decontamination attempts. The derived limits for publicly accessible areas are often quoted from the Medical & Dental Guidance Notes and vary depending upon the radionuclide.
Dual probe	a radiation detector probe which can be used to make independent measurements of two different types of radiation e.g. alpha and beta.
Energy compensated (as applied to detectors)	the process of adjusting the response characteristic of a detector system such that the measured response is relatively independent of the energy of the radiation over an identified range.
Emission probability	the probability that a particle or quantum (specified by type and energy) will be emitted when one nucleus of the radionuclide disintegrates

Fail to danger	the behaviour of a detector system whereby the indication reduces as the radiation intensity increases. In extreme cases, the indication may drop to zero at very high exposure rates.
Function-check source	an uncalibrated source which causes the detector to indicate a response above background. Often used to test such items as alarm level settings, etc.
Industrial radiography sources	radioactive sources, usually of very high activity, that are used to identify defects in materials (such as in welds) by comparing differences in transmission efficiencies.
kVp	the maximum, or peak, potential difference applied to an X-ray tube between the anode and cathode.
Linear accelerator (Linac)	a particle accelerator which accelerates electrons, protons, or heavy ions in a straight line by the action of alternating voltages.
Mössbauer spectroscopy	the measurement and analysis in crystalline solids of small shifts in nuclear energy levels that correspond to gamma ray emission and resonant reabsorption frequencies.
Mu-metal	A nickel-iron alloy used for shielding against magnetic fields.
Polar response	the directional response of a detector, usually measured at ± 90° to its horizontal plane about its reference point.
Pulsed radiation	machine-generated ionising radiation which is emitted in a repetitive on/off sequence. The ‘on’ period may be of a very short duration, perhaps only microseconds.
Scattered radiation	the ionising radiation resulting from the interaction of the radiation, from the primary source of radiation, with a scattering medium, such as shielding, air, etc. The scattered radiation is normally reduced in energy compared with that from the primary source and may appear to come from a different direction.
Self-absorption	the absorption of the ionising radiation emitted from a radioactive source by the source material itself.
Sky shine	scattered radiation arising from scattering interactions with the air surrounding the source. This is also important for neutron radiation.
Smart (as applied to detector systems)	a system which recognises the type of probe which is connected and applies the appropriate calibration factors.

Spectral degradation	the process whereby the mean energy of the spectrum of scattered radiations is less than that of the original spectrum of radiations.
Time constant (of an instrument response)	a measure of the time before the indicated response of an instrument reaches a given percentage of true response (often taken as 90 %).
Traceability	the property of a result of a measurement whereby it can be related to appropriate standards, generally international or national standards, through an unbroken chain of comparisons.